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COMPARISON OF SOIL SUCTION AND ONE-DIMENSIONAL CONSOLIDATION CHARACTERISTICS OF A HIGHLY PLASTIC CLAY

BY

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ABSTRACT

Investigation of the shrinking and swelling action of highly plastic clays on the prairie provinces has been carried out for several years by the National Research Council of Canada. The problem facing engineers associated with the building industry is the lack of an analysis whereby the probable amount of vertical movement of a building can be predicated. Research into one phase of the problem was undertaken in this thesis.

A literature review of research work in countries such as England, South Africa, Australia, Israel and United States was conducted and a study made of the two analyses which have been developed. One analysis was developed by Croney et al in England, based on the suction test and the other by Jennings in South Africa, based on the one-dimensional consolidation test.

For the work of this thesis, several pieces of equipment were used to measure soil suction. A testing program was organized which involved the determination of soil suction throughout the complete drying range for Regina Clay. A comparison was made between the results of the suction test and the conventional one-dimensional consolidation test.

For a saturated soil the virgin compression branch is the same for both the suction and consolidation tests as long as the degree of saturation is close to 100 per cent. The recompression branch of the suction curve has a gradual curvature onto the virgin compression branch. The reason for this difference is believed due to either the difference in structure induced by consolidation or friction between the ring and

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GLOSSARY OF TERMS AND SYMBOLS USED IN THIS THESIS

Terms

Capillary Tube Analogy - Rise of water in an ideal capillary tube due to the surface tension of the water.

Desiccated - Considered to be a state such that the water content of the soil mass will increase when the surface of the soil is covered with an infinite, impermeable, weightless membrane.

Dispersed Structure - The structure of a soil mass when the particles resume approximately parallel positions.

Double Oedometer Test - Two one-dimensional consolidation tests performed on similar samples where one sample is allowed free access to water while the other is performed in its natural water content state.

Effective Stress Principle - The behavior of a soil can be predicted in terms of effective stress, which is equal to the total stress minus the pore water stress for a saturated system or the total stress minus a ratio of the pore fluid stresses for a partially saturated system.

Flocculated Structure - The structure of a soil mass when the particles exhibit an edge-to-face contact.

Free Swell Consolidation Test - One-dimensional consolidation test in which free access of water to the soil is allowed while only a small surcharge is placed on the sample.

Fluid Phase - The combination of the water and air of a partially saturated soil system.

Natural Water Content Consolidation Test - One-dimensional consolidation test in which the sample is consolidated in an atmosphere of 100 per cent relative humidity and no water surface comes in contact with the sample.

Pore Water - All the free water in the clay-water system.

Pressure Membrane Extractor - Apparatus to measure soil suction in the range of approximately 0.5 to 15 kg/cm^2.

Pressure Plate Extractor - Apparatus to measure soil suction in the range from zero to one kg/cm^2.

Relative Vapor Pressure - The ratio of the vapor pressure above a water surface when the water is in a state of tension to the vapor pressure under atmospheric conditions.

Soil Suction - The difference between the pressure of the pore water and atmospheric pressure and is a measure of the surface forces retaining water in the soil structure.

GLOSSARY OF TERMS AND SYMBOLS USED IN THIS THESIS (Continued)

Specific Bulk Volume - The ratio of the total volume of a soil mass to its dry weight of soil solids. It is the reciprocal of dry unit weight, usually expressed as a percentage.

Suction Test - Laboratory test to measure the soil suction characteristics.

Transpiration - The evaporation of moisture from the leaves of a plant and the uptake of moisture from the soil by the plant roots.

Symbols

e - void ratio

F - capillary force

h - length of drainge path in consolidation or suction test

H - distance from the soil surface to the water table

k - coefficient of permeability

M - molecular weight of water

P - applied pressure

p - vapor pressure over a curved water surface

p_o - vapor pressure of free water at atmospheric conditions

p'' - soil suction

R - universal gas constant

R.H.- relative humidity

S - degree of saturation

T - absolute temperature

T_s - surface tension force

t_{50}- time required to reach theoretical 50 per cent consolidation as determined by the graphical construction from the logarithm of time fitting method

u - pore fluid stress

GLOSSARY OF TERMS AND SYMBOLS USED IN THIS THESIS (Continued)

z - depth below the soil surface

σ' - effective stress

σ - total stress

γ_w - unit weight of water

γ - bulk wet density

α - angle of contact between water and the capillary tube material

χ - factor signifying the ratio between the pore fluid stress and soil suction

CHAPTER I

INTRODUCTION

1:1 General

Increasing interest has been shown in recent years to understand the behavior of soils exhibiting high swelling characteristics. Soil minerals, especially those of colloidal size, attract water by means of electrochemical forces. The mechanism by which water is held has undergone much investigation by colloidal chemists, soil physicists and engineers. Colloidal chemists (Cooling, 1960)[1] speak of it as depending upon such factors as surface intensity of charge on the soil particle, electrolyte concentration, distance from particle surface, various effects of particle shape and arrangement, and external stress influences. Soil physicists refer to the affinity of soil for water in terms of the difference in the free energy per unit mass of the soil water and that of pure water at a standard reference level. Research engineers such as Lambe et al, (1959) and Thomson, (1963) have used the above mechanisms in the study of practical problems of importance to soils engineers. A microscopic phenomena occurring in a soil must be placed on a macroscopic scale in order to become of practical use and this has been done by the "effective stress principle."[2*] Whether the stress mechanism in a highly

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[1] References listed alphabetically in "List of References."

[2*] Indicates expressions explained in "Glossary of Terms and Symbols."

swelling clay can be spoken of in terms of effective stresses has been questioned but, despite difficulties, it appears to be the best available means to explain volume changes (Lambe et al, 1959).

Problems encountered with expansive soils may be divided into two main categories. The first deals with changes in shear strength with time and has received attention in Alberta in connection with landslides in over-consolidated clays (Hardy et al, 1962). The second category deals with the amount of volume change or vertical ground movement which can occur with time in a soil mass. This thesis is concerned with this phase of the problem.

Surficially in Western Canada there are lacustrine deposits which exhibit large volume changes during wetting and drying. Movements of engineering structures placed on these highly plastic clays pose a serious problem to soils engineers (Baracos and Marantz, 1952; Baracos and Bozozuk, 1957; Hamilton, 1962). Analysis of the problem is very complex due to the many factors involved and their unpredictable nature. For example the soil of concern is usually partially saturated and the factors affecting a water content change are controlled by climate.

1:2 Previous Research

The Division of Building Research of the National Research Council of Canada (NRC) undertook to investigate the magnitude of the problem in terms of the amount of vertical ground movement and the resulting cost to the building industry. The writer was associated with the problem during the summers of 1962 and 1963 during employment with NRC. Many situations were investigated and the following two cases will help

illustrate the problems encountered.

The elementary school at Eston, Saskatchewan, was built in 1924 on a highly plastic clay soil. Since that time the maximum total vertical movement has been in excess of thirty inches. Each time the differential heave was in the order of eight inches, the floor was torn out, soil was excavated and a new floor constructed. This has been done at least three times during the life of the building and is in need of being done again. The second example is an industrial warehouse built in Regina, Saskatchewan, during the summer of 1961. The floor slab was placed on grade and within one year a maximum differential heave of 3.5 inches resulted. Investigation into the reason for such rapid heave revealed that a leak in the plumbing system had supplied water to the soil beneath the slab resulting in expansion of the clay. A more detailed account of the above examples is in Appendix A.

An extensive literature review has been carried out on information related to the heaving problem. The material, much of which has been collected by the National Research Council, was from various countries of the world and indicated the methods which have been used to cope with the problem. It was felt that much duplication could be avoided by obtaining a coherent picture of previous research.

The literature review revealed that the main problem facing the soil mechanics engineer was the lack of a method whereby the amount of heave which might occur to an engineering structure could be predicted. Research has been conducted in various countries and some of the outstanding workers are Jennings and Burland in South Africa, Croney, Coleman and Black

in England, Aitchison in Australia, Zeitlen and Polonsky in Israel and Seed and Lambe in United States. Although much has been accomplished, many problems have been encountered. The literature survey revealed that different approaches have been taken to the problem and two of them appear promising for use in the building industry. One of these analyses was developed in England and is based on results from the suction test.* The other analysis was developed in South Africa and is based on the one-dimensional consolidation test. Both methods have been employed in practice to a limited extent in their respective countries. Apparent lack of liason between research workers has limited comparison of the methods or the results obtained. Since it would be desirable for soil engineers in Canada to have a method of predicting heave at their disposal, it would seem beneficial to investigate further the analyses set forth by various authors in the light of Canadian soils. In over-consolidated clays in Western Canada, the problem occurs without any known method for predicting total heave (Peterson and Peters, 1963).

1:3 The Problem

This thesis has been limited to the study of the two analyses previously mentioned because of the broad scope of the heaving problem. The main difference in the analyses is the laboratory test upon which they are based. Surprisingly, there appears to be a lack of specific literature which deals with the relationship between the suction test and the standard one-dimensional consolidation test. Many questions can be asked concerning the above analyses such as, "How do the results from the two methods compare?" - "On what points are they similar and how do they differ?" - "Is the difference significant?" - "Can the effective stress theory be applied

to both analyses?". A basic consideration which would lead to satisfactory answers to these questions concerns the relationship between the suction test and the standard one-dimensional consolidation test.

There appears to be considerable confusion among engineers over the term "soil suction"*. First, there has been confusion about its meaning which has resulted from various groups of workers, such as colloidal chemists, soil physicists and engineers, defining it with reference to different properties. Secondly, the significance of soil suction and its interpretation with regard to engineering problems does not appear to have been fully understood. Only limited work has been done to explain soil suction in terms of neutral and effective stresses. At present, engineers have treated soil suction as a unique characteristic, dependent only on particle size and initial density (Black et al, 1958).

There have been different opinions regarding the approach which should be taken in solving the heaving problem. The two procedures previously mentioned are the main approaches which have been taken but some investigators feel that neither approach is satisfactory for engineering purposes. Williams (1963) stated "....the negative pressures existing in a desiccated profile may bear no relationship to the position of the water table." He felt that research should be directed towards measurement of actual soil suction profiles. Aitchison and Holmes (1961) have advocated an approach similar to that of Williams. Coolings, in commenting on Aitchison's and Holmes' approach stated, "Before this approach can be accepted there is need for much more evidence derived from practical examples where comparisons have been made between actual and predicted movements." In order to formulate an opinion regarding the approach

which should be taken towards the solution of the problem, it is of prime importance to have a clear understanding of the stresses in the soil mass for all cases under consideration. This thesis will consider in some detail the two present analyses and, in particular, will base discussions upon the principle of effective stresses.

Essential to the comparison of Croney et al's and Jennings' analyses is the comparison of the suction and consolidation test. Jennings (1960) expressed what he felt would "probably be obtained when similar soil samples were compressed under externally applied pressures and under applied suction pressures." He shows that soil suction and positive pressure result in equal equilibrium water content conditions in the low pressure range with divergence occurring at higher suction and positive applied pressures. However, there are no numerical values on the diagram used by Jennings to show these relationships which make it impossible to determine the range of pressures to which he may be referring. Most research workers have either inferred or assumed, that results from the suction and consolidation test were equal at saturated or near-saturated conditions. Croney and Coleman (1952) suggest that for saturated compressible clays, the pressure void ratio curve determined by the consolidation technique is in fact a suction moisture content drying curve. Aitchison (1961) is the only reference known to the author which shows experimental results on the comparison of soil suction and effective stress. The results were found to be very similar as long as saturation was approached. Only two sets of results substantiate this point over a limited pressure range and it was felt that further tests under closely controlled conditions should be performed for a highly plastic clay from Western Canada.

1:4 Scope of Investigation

The investigation that forms the basis of this thesis compares the volume, water content and soil suction characteristics of a soil with those obtained from the standard one-dimensional consolidation test on the same soil. Consideration was also given to the comparison of the rate of consolidation occurring in the suction and consolidation test. Since the drying process occurring in the suction test is believed to be similar to drying by evaporation of water from the soil surface, a comparison was made of the volume versus water content relationship for both methods of drying.

Apparatus which measures soil suction is not common equipment in soils mechanics laboratories in Canada and it was necessary to either obtain or develop suitable equipment. A pressure plate extractor* and a pressure membrane extractor* were obtained from the Agricultural Engineering Department at the University of Saskatchewan, Saskatoon, but a new apparatus had to be developed incorporating the measurement of the rate of consolidation in the suction test. This new apparatus was developed for more practical purposes from the engineering standpoint and has several advantages not available in previous equipment.

Only one soil, a high swelling clay which has presented problems in Saskatchewan, was chosen for the testing program. However, a large number of tests were performed to assure confidence in the results. Extension of the testing program to include soils of different plasticities and degrees of saturation was considered outside the scope of this thesis but is recommended for future research.

CHAPTER II

THE SHRINKING AND SWELLING PROBLEM

2:1 General

The shrinking and swelling sction of a highly plastic clay has been described by colloidal chemists in terms of the ability of a soil particle to hold water on its surface. Soil physicists speak of the 'held' water in terms of the difference in the energy conditions of the water in the soil and that of a standard state of reference. It has become apparent to engineers that it is inadequate to use water content as a criterion for describing soil moisture movement. Croney et al (1958) stated - "Moisture content does not (therefore) provide the gradient responsible for liquid flow." He goes on to say that it appears more reasonable to describe the volume change of a soil in terms of stress in the fluid phase* rather than the weight of water. If water is added to a soil when the fluid phase is in a state of tension, the affinity of the soil for water is reduced and the tension in the fluid phase is decreased. A tension decrease in the fluid phase results in a decrease of the effective stress which in turn results in a volume increase of the soil mass. There may be, however, exceptions to the above explanation such as the case where a breakdown in the soil structure of a partially saturated soil occurs when water is added to the soil mass (Jennings et al, 1963).

2:2 Causes of Change in Water Content

Changes in water content associated with the problem of shrink-

ing and swelling are of a more unpredictable nature than those usually encountered in soil machanics. The main factors are controlled by climate and vegetation. The causes of water content changes can be divided into two categories, namely, those which cause a decrease and those which cause an increase in moisture conditions.

Causes of moisture decrease may be considered as:

(i) Evaporation from soil surfaces which is often manifested by cracking of the surface.

(ii) Transpiration by plants, particularly from water-loving trees, such as poplars, or from deep-rooted grasses and crops such as alfalfa.

(iii) Subsurface heating under structures, especially where large furnaces are involved.

Causes of moisture increase may be considered as:

(i) Infiltration of rain and snow melt.

(ii) Breaks in subsurface drains or water mains, tending to concentrate water locally in the subsoil.

(iii) Leakage of other hydraulic structures such as reservoirs and canals.

(iv) Capillary rise and accumulation of moisture from a water table under an impervious covering.(Including movement in the vapor phase).

(v) Intense local garden watering and irrigation.

(vi) Poor surface drainage including runoff from roofs, tending to concentrate water in surface pools from which it seeps into the ground.

The engineer associated with the building industry often finds vertical movements occurring in a structure after construction is completed. The movements result from a disturbance of the previously existing soil moisture regime. Sometimes the new equilibrium soil moisture regime does not differ sufficiently from the original regime to harm the structure, while in other cases movements may cause damage to the structure. Giving consideration to cases related to climate, the direction and amount of vertical movement which might occur are dependent upon the relative importance of such factors as transpiration,* evaporation and infiltration. Aitchison (1961) reported that in Southern Australia where the climate is humid, shrinkage occurs after an impervious membrane is placed on the soil. The dominant factor in this situation is the amount of infiltration and since a limitation is placed on the rainwater available a net downward movement of water results in settlement. In Western Canada the climate is generally semi-arid, and transpiration by plants and evaporation of water from the surface of the soil are the dominant factors. The usual case involves the placement of a structure upon a desiccated* soil which has been dried by transpiration and evaporation. When the vegetation is removed and a relatively impermeable structure placed over the area, transpiration and evaporation are inhibited and a net upward movement of water results in a moisture gain beneath the structure. Since lateral swelling is restricted by adjacent soil, heave takes place in a vertical direction.

2:3 Stresses Developed in a Soil Mass Due to Transpiration, Evaporation and Infiltration

The thermodynamic approach has been applied to a movement of moisture in a soil mass and has shown that moisture movement is the result

of a stress gradient in the water phase (Croney et al, 1958). The stresses in the water phase caused by transpiration, evaporation and infiltration are of prime importance in the study of the distribution of soil moisture.

The removal of moisture from a soil mass by transpiration and evaporation places a tensile stress upon the water phase. As long as the soil remains nearly 100 per cent saturated, the effective stress theory for a two phase soil system should apply (Penner, 1959). Therefore, a decrease in pore water stress causes an increase in effective stress. Also, if moisture is added by infiltration, to a soil mass which exists with a tensile stress in the water phase, an increase in pore water stress and a decrease in effective stress results.

The means by which tension is placed on the water phase of a soil has been explained by agricultural workers and will only briefly be described here (Buckman and Brady, 1962). The process of transpiration involves the evaporation of moisture from the leaves of a plant and subsequent movement of water from the soil into the roots and up through the plant. In order for moisture to move from the soil into the plant the energy potential in the plant must be lower than that in the soil (Gardiner, 1961). In other words, the suction of the plant must be greater than the soil suction if the plant is to take up moisture. As the soil dries, the soil suction increases and the plant must exert a greater suction in order to obtain water. However, the suction of plants is limited by the osmotic pressure of the leaf cells which is in the order of 25 to 100 kilograms per square centimeter. Numerical relationships associated with transpiration are very complex as can be shown by the qualitative

description of plant behavior. Plants draw moisture more rapidly from the surface layers because of the greater number of roots in this zone. With further drying the deeper roots may draw moisture from lower layers at relatively low suctions.

Evaporation at the surface of a soil mass proceeds at a rate depending upon the temperature, relative humidity and wind velocity of the surrounding atmosphere. Evaporation from a soil mass comes to equilibrium with the surrounding air at a relative humidity which is a function of the tension in the water (Terzaghi and Peck, 1960). Water existing in a state of tension ceases to evaporate at a lower value of relative humidity than under atmospheric pressures. The relationship between the vapor pressure corresponding to any state of tension in the water andthat of atmospheric conditions is designated as the relative vapor pressure of the water. Evaporation from a soil surface ceases when the relative vapor pressure at the soil surface is equal to the relative humidity of the surrounding air. The air-water boundary of a soil mass takes the form of water menisci which induces tension in the water phase. The capillary tube analogy* shows the mechanistic picture of the development of tension in the water phase of a soil and is outlined later in THEORY.

The distribution of stresses in a soil profile and the changes which can occur due to transpiration, evaporation and infiltration are of prime importance in the understanding of the phenomena of heave. To illustrate the relative effects of transpiration, evaporation and infiltration, the following example is cited. A soil mass is assumed to be initially saturated, intact, and have a water table at a distance, H, below the soil surface. For the condition of no flow of water, as shown in

FIGURE 1a, the pore water pressure at a point below the surface of the soil is directly related to its height above the water table (Jennings and Kerrich, 1962). At any depth down to the water table, the pressure in the pore water is negative and can be written numerically as

$$u = - \gamma_w (H-z)$$

where u = stress in the pore fluids. For partially saturated soils it represents the combination of stress in the water and air.

γ_w = density of water

z = depth below soil surface

H = distance from soil surface to water table

In a saturated soil mass the negative pore water stress is equal numerically but opposite in sign to the soil suction and is designated by the term p". The effective stress at any depth is

$$\sigma' = \sigma - u = \gamma z - \gamma_w (z-H)$$

where σ' = effective stress

σ = total stress

γ = bulk soil density

FIGURE 1b, shows the new equilibrium pore water pressure conditions if a constant evaporation is imposed which is not large enough to cause cracking or entry of air into the soil mass. The pore water pressure versus depth relationship is still linear and lies to the left of the previous pore water pressure line. Several other noteworthy observations arise as a result of evaporation. Since the effective stress of the soil mass is increased, consolidation occurs resulting in a settlement of the surface. A drop in the level of the water table may occur due to the up-

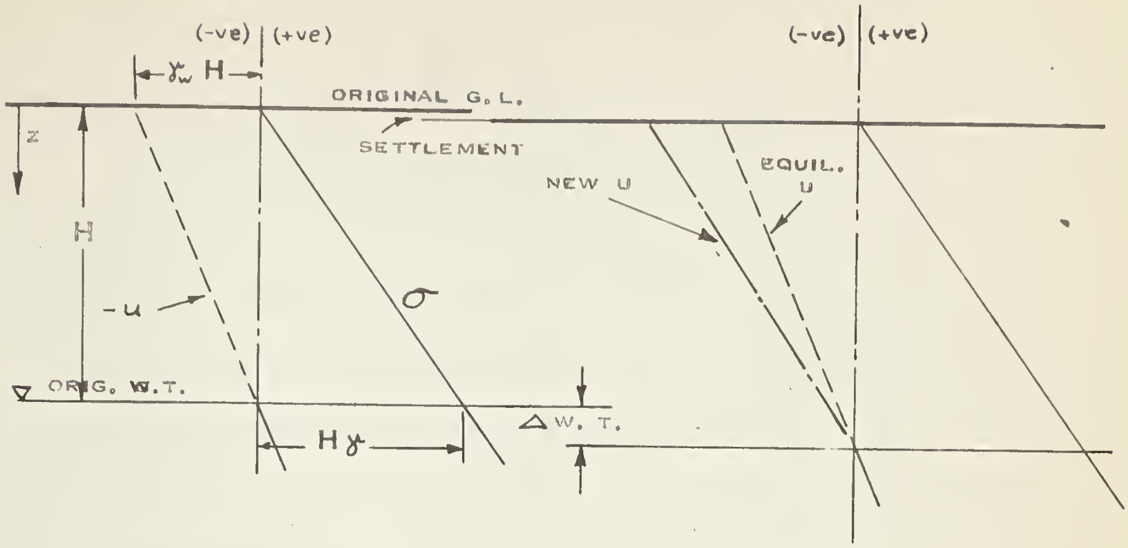


FIGURE 1A

NO EVAPORATION FROM SURFACE

FIGURE 1B

WITH EVAPORATION SMALL ENOUGH SO NO AIR ENTRY OR CRACKING OF THE SOIL OCCURS.

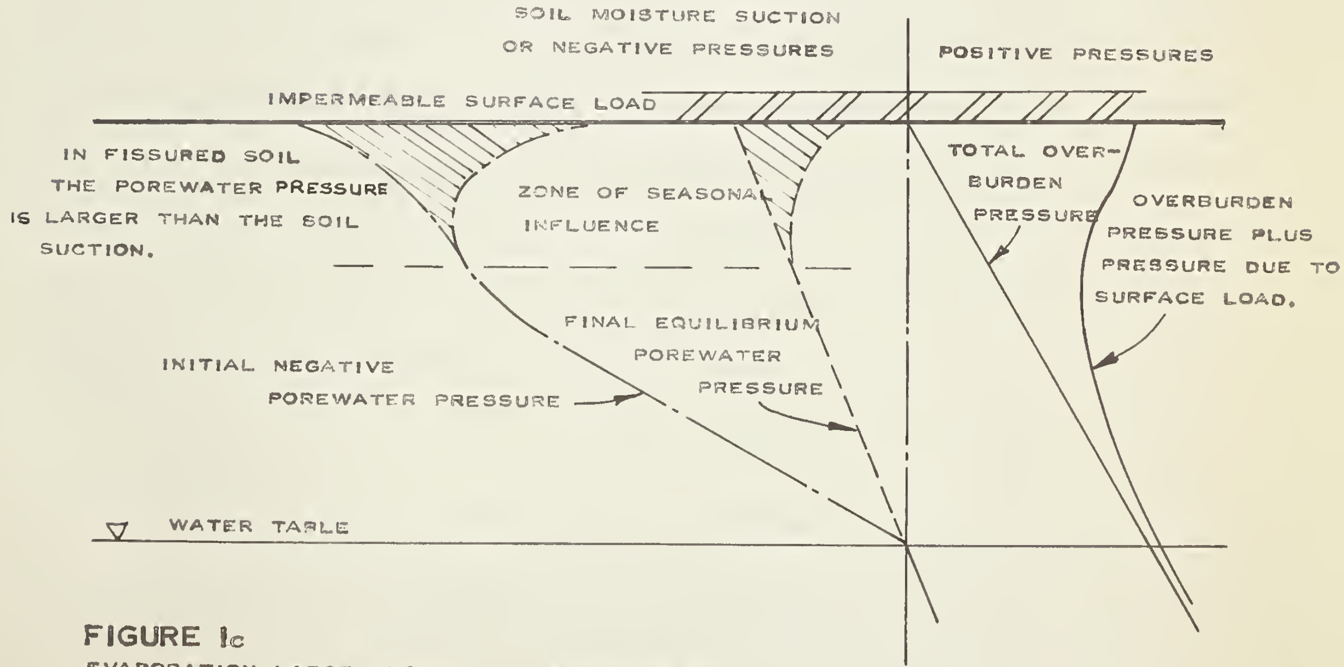


FIGURE 1C

EVAPORATION LARGE ENOUGH TO CAUSE AIR ENTRY AND CRACKING OF THE SOIL.

FIGURE 1 – STRESSES ACCOMPANYING THE DEVELOPMENT OF DESICCATION IN A SOIL MASS.

ward flow of water. The total horizontal stress above the water table is reduced, placing a negative stress upon this part of the profile which may result in vertical cracks. Further evaporation results in more settlement, lowering of the water table and an increase in horizontal tension. Transpiration by plants adds to the tension stress in the pore water but does not have a linear or regular relationship between depth and pore water stress. If the tension in the pore water becomes large enough, the soil becomes partially saturated in which case the soil suction become smaller (more negative) than the pore fluid stress. The relationship between pore fluid stress and soil suction is

$$u = \chi p''$$

where χ = a factor between 0 and 1.0

The effect of placing a covering such as a building upon the soil again modifies the stress conditions as shown in FIGURE 1c. Due to the weight of the building an additional stress is added to the total stress. However, the prevention of evaporation and infiltration of rain result in an accumulation of moisture which increases the pore water pressure. The end condition is a reduction in effective stress which results in an increase in the volume of the soil mass. The amount of heave which occurs to the building depends upon the magnitude of the initial and final stress conditions in the soil mass.

CHAPTER III

THEORY

3:1 General

The study of the shrinking and swelling action of highly plastic clays is associated with three relationships which are of concern to the soils engineer. They are the relationships between volume and water content, volume and effective stress, and water content and effective stress. Once the relationships among these factors are understood they can be put to practical use.

The theoretical questions arising from the objectives of the experimental program are, "Does the suction or the one-dimensional consolidation test more closely assimilate the behavior of a soil which is subjected to factors such as transpiration, evaporation and infiltration?" or "Do both tests adequately describe equilibrium water content conditions in the field?" The consolidation theory is outlined in most soil mechanics text books (Terzaghi, 1943) and is only briefly dealt with in this chapter. The theory involved in the suction test is outlined in considerable detail in this chapter along with a comparison of the procedure and theory of the suction test with that of the one-dimensional consolidation test.

3:2 The Drying of a Soil Mass

The processes by which the water content of a soil mass are

modified can be divided into two main categories. The water content can be changed by applying a stress to the soil structure or by applying a stress to the pore fluid of the soil mass. The former situation has been outlined by Terzaghi (1934) and is known as the consolidation theory. Drying of a soil by transpiration or evaporation applies a stress to the water phase. Consolidation of the soil mass occurs until the effective pressure in the soil can resist the stress applied to the water phase.

The relationship between volume and water content for the cases of stress applied to the pore water and stress applied to the soil structure are shown in FIGURE 2. Both relationships are the same as long as the soil remains saturated. In the consolidation test, no air can enter the soil regardless of the applied load. However, the drying process in which stress is applied to the pore water can be divided into two stages (Jumikis, 1962). In the first stage evaporation causes a translocation of moisture from the interior to the exterior of the soil, resulting in a volume change equal to the water content change. The second stage is encountered when air begins to enter the voids of the soil, thus making the change in volume less than the change in water content. This gives rise to a curved relationship between volume and water content changes and signifies that the soil is partially saturated.

3:3 Capillary Tube Analogy

The capillary tube analogy can be used to describe the drying process occurring in the suction test. Fine-grained soils are capable of holding water in a state of tension for an indefinite period of time. In order to explain this phenomenon there must exist a force which is cap-

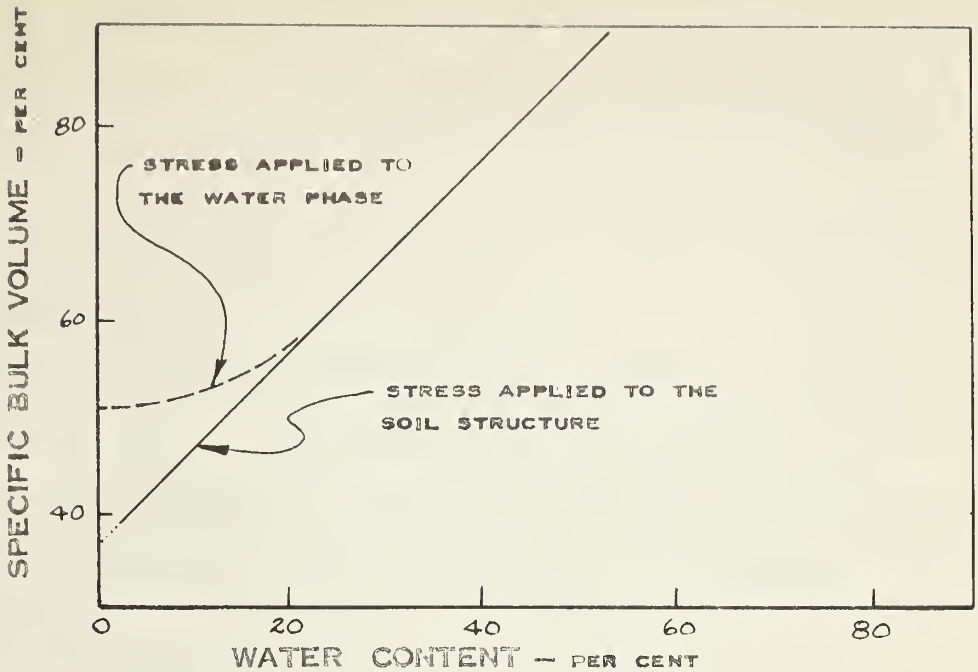


FIGURE 2 BULK SPECIFIC VOLUME VERSUS WATER CONTENT FOR CASES OF STRESS APPLIED TO THE WATER PHASE AND TO THE SOIL STRUCTURE.

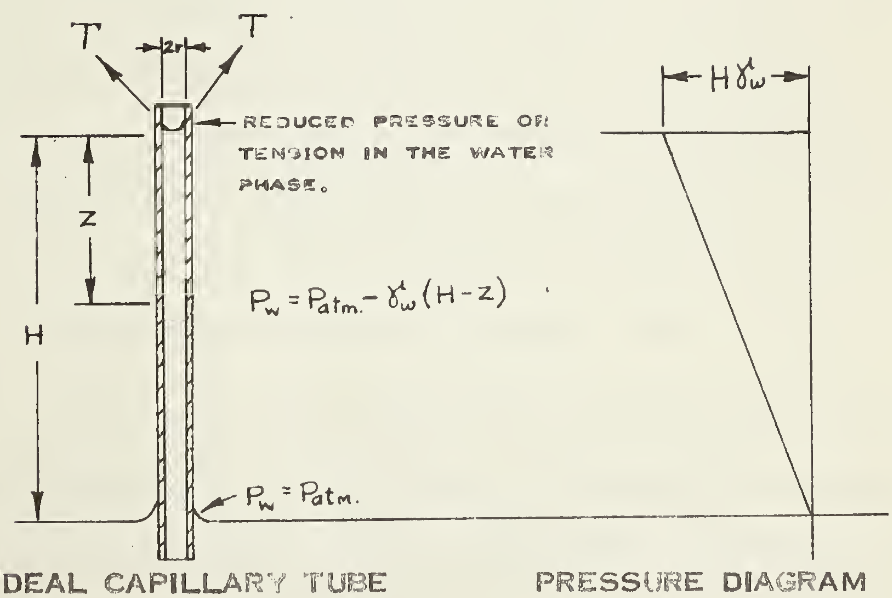


FIGURE 3 PRESSURE VARIATION ASSOCIATED WITH THE RISE OF WATER IN AN IDEAL CAPILLARY TUBE.

able of compensating for the tension force in the water. Although the physical nature of the force acting is not fully known, it is termed a capillary force which is related to the surface tension effects of water.

The height of rise of water in an ideal capillary tube depends on the radius of the tube, the chemical composition of the walls of the tube and the chemical composition of the solution in the tube (FIGURE 3) (Terzaghi, 1943). Since water rises in the tube and the system is in equilibrium, there must be some force tending to hold the water up. The vertical component of this force is equal to the weight of water above the water table.

Mathematically $F = \pi r^2 \gamma_w (H-z)$--------------1.)

where F = force holding water up

r = radius of capillary tube

The magnitude of this force may be very large, making it necessary to conceive that the mechanical properties of water in the uppermost layers of the column are different than ordinary water. Although there has been no known agreement on the molecular mechanism which produces surface tension, there need be no alarm because "no capillary phenomena has ever been observed which is incompatible with the mathematical concept of surface tension" (Terzaghi, 1943).

The surface of the water in the capillary tube forms a meniscus, its shape depending on the angle of contact between water and the tube material, and the radius of the capillary tube. Equilibrium conditions require that the capillary force is:

$F = T_s 2\pi r \cos\alpha$ --------------2.)

where T_s = surface tension of the liquid. For water it is 0.073 grams per centimeter at 20°C.

α = angle of contact between water and tube material. The angle is zero degress for a clean, moist glass tube and water.

Equating equations 1.) and 2.) gives:

$$H-z = \frac{2T_s\ (\text{Cos}\ \alpha\ )}{r\ \gamma_w} \text{--------------3.)}$$

The entire column of water exists in a state of tension which is proportional to the distance above the water table, hence the pore pressure can be written:

$$u = -\ \gamma_w\ (H-z)\text{--------------4.)}$$

The equilibrium vapor pressure over a curved water meniscus is reduced below the vapor pressure of free water as a result of tension at the water surface (Penner, 1959). Therefore, the relative vapor pressure is a direct measure of the forces operative in holding the water in the capillary tube. The relationship between relative vapor pressure and the radius of curvature of the water meniscus is given by the Kelvin equation:

$$\ln p/po = -\ \frac{2T_s\ M}{r\ \ _w\ RT} \text{--------------5.)}$$

where p = the vapor pressure over the curved surface,

p_o = the vapor pressure of free water,

M = the molecular weight of water,

R = the Universal gas constant,

T = the absolute temperature.

To place the above formula in more practical terms, vapor pressure

can be expressed in terms of relative humidity and the capillary force in terms of kilograms per square centimeter.

$$\text{Relative Humidity (R.H.)} = \frac{100p}{p_o} \text{ --------------6.)}$$

and $$u = \frac{2T_s}{r} \text{ --------------7.)}$$

Therefore, substituting 6.) and 7.) into 5.) gives:

$$u = \frac{RT}{M} \ln \text{(R.H.)} \text{--------------8.)}$$

The relative humidity of vapor above the water meniscus approaches 100 per cent for water tensions less than 10 kilograms per square centimeter but for larger values of water tension it varies from 0 to 99 and has proven to be a useful method for the measurement of large pore water tensions.

The capillary model as set up in preceding paragraphs is used herein to explain the development of negative stress in the pore water and the consolidation of a soil mass. It closely assimilates the drying of a soil due to evaporation (Haefeli et al, 1948).

Based on the premise that volume change is a manifestation of a change in effective stress, it would appear from a theoretical viewpoint that for a saturated soil an increase in pore water tension causes essentially an equal increase in effective stress. If this is true, it can be reasoned that it should be possible to apply Terzaghi's consolidation theory to cases where a tensile stress is applied to the water phase. As stated previously, it is proposed that a series of suction tests (application of tensile stresses to the pore water) and standard consolidation tests be carried out and a comparison of the data derived will confirm or

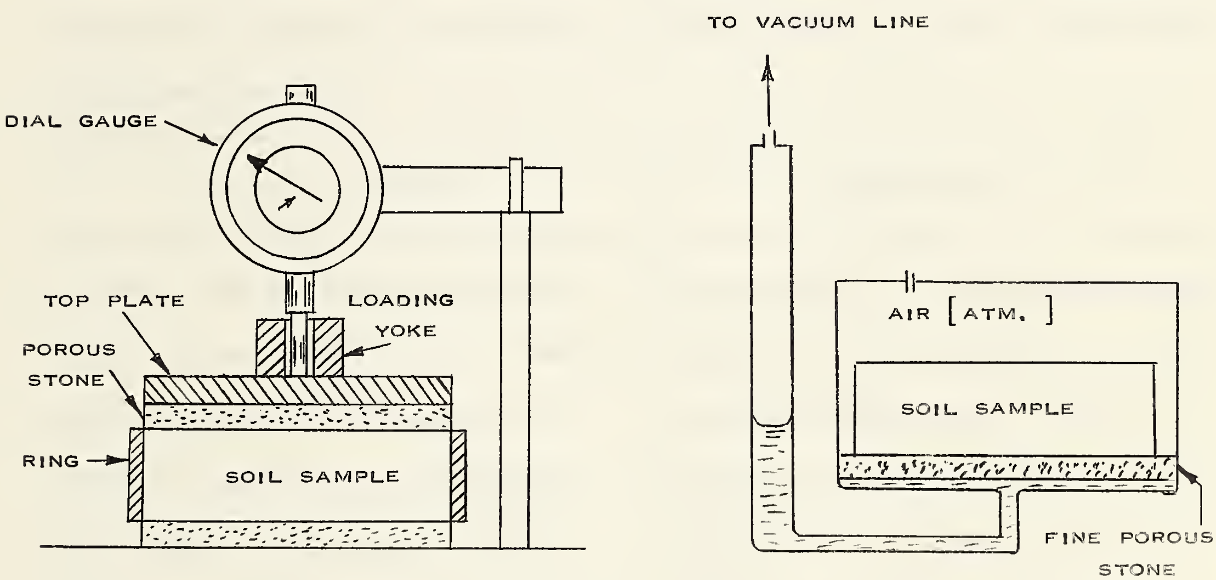
deny the preceding hypothesis.

3:4 Comparison of the Theory and Procedure for the One-dimensional Consolidation Test and the Suction Test

Several similarities and differences occur between the theory and the procedure of the consolidation and suction test. A comparison is presented in the following Tabular form:

CONSOLIDATION TEST	SUCTION TEST

FIGURE 4. Diagrammatic View of Apparatuses



CONSOLIDATION TEST	SUCTION TEST
External positive load is applied to the soil sample through a porous stone.	Load is applied to the water phase of the soil sample either by a positive air pressure in the chamber above the sample or by a negative

	pressure on the water below the sample. Either method gives similar results (Richards and Fireman, 1943; Penner, 1959) but for high soil suctions it is necessary to resort to the former method.
Changes in water content are associated with one-dimensional consolidation and drainage in two directions.	Water content changes are associated with three-dimensional consolidation but drainage is from one surface of the sample.

Assumptions Involved in the Theory of Consolidation and Their Application to the Suction Test.

Consolidation Test	Suction Test
1) The voids of the soil are completely filled with water. Consolidation is defined as decrease of the water content of a saturated soil without replacement of the water by air, (Terzaghi, 1934).	If the soil is initially saturated, there will be no entrance of air into the sample until a point is forced to retreat between the soil particles. The water content at this point is usually below the plastic limit which corresponds to high capillary tensions (Jumikis, 1962). The application of Terzaghi's consolidation theory will be attempted only for the range in which the soil remains saturated.

2) Both water and the solid constituents are incompressible.	Incompressibility of water and solid constituents is applicable for the suction test also although a small amount of air in the water phase may result in a considerable volume change when the water is under tension (Gilbert, 1959).
3) Darcy's law is valid.	Darcy's law is assumed valid since the hydrostatic gradient causing flow is independent of the sign of the pressures.
4) The coefficient of permeability is assumed to be constant for the pressure increment under consideration.	A constant coefficient of permeability is just as applicable. However, there may be a slight difference in its value due to a diference in soil structure induced by three-dimensional consolidation.
5) The time lag of consolidation is due entirely to the low permeability of the soil.	The assumption of the time lag being due to the low permeability should be more realistic since there is no side friction involved between the specimen and the walls of the ring. Also, secondary consolidation may be less significant in three-dimensional consolidation

	which means the assumption is more correct for the suction test than the one-dimensional consolidation test (Hardy, 1963).

Mechanics of Consolidation in the One-Dimensional Consolidation Test and the Suction Test

When either a positive pressure is applied to the soil mass or negative pressure is applied to the water phase of a soil mass, water escapes from the pores. This process involving a slow escape of water results in a gradual consolidation and a pressure adjustment. Therefore, a change in applied pressure results in a change in water content. To simplify the theory of consolidation, a portion of the pressure versus water content curve can be assumed to be a straight line relationship which holds under all conditions and does not vary because of time effects or any other factor (Taylor, 1948). It must be realized that for a highly plastic clay the effects of plasticity lag which are of major importance are being neglected. The processes of consolidation for the one-dimensional consolidation test and the suction test can now be explained on the basis of the above simplified relationship.

ONE-DIMENSIONAL CONSOLIDATION TEST	SUCTION TEST

FIGURE 5a. - Before the application of a pressure

Just before the application of a positive pressure, a sample has an	Before the application of a pressure the sample has an effective pressure,

ONE-DIMENSIONAL CONSOLIDATION TEST

SUCTION TEST

NOTE— DRAINAGE AT BOTTOM OF SAMPLE ONLY

TOTAL NEUTRAL EFFECTIVE TOTAL NEUTRAL EFFECTIVE

FIGURE 5A BEFORE THE APPLICATION OF A PRESSURE

FIGURE 5B THE INSTANT AFTER THE APPLICATION OF A PRESSURE

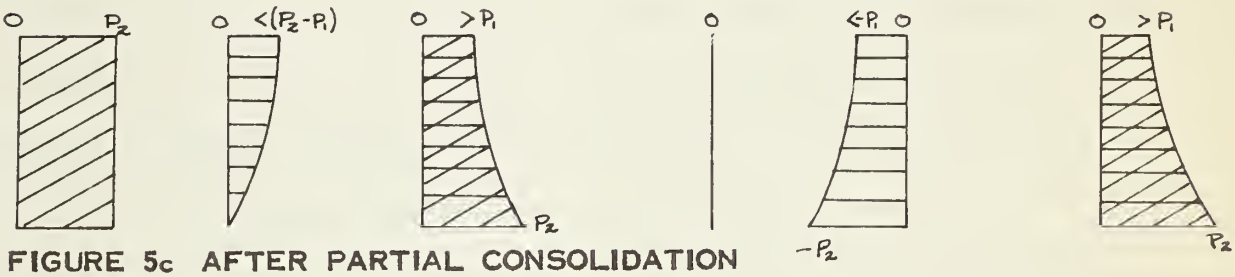


FIGURE 5C AFTER PARTIAL CONSOLIDATION

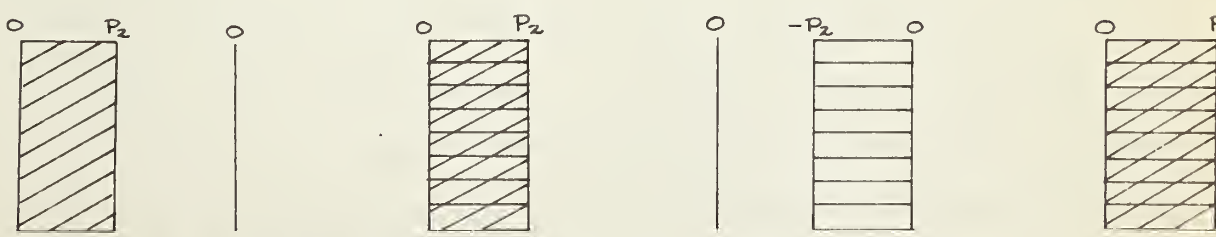


FIGURE 5D AFTER COMPLETE CONSOLIDATION

FIGURE 5 STRESS CHANGES DURING THE CONSOLIDATION PROCESS IN THE ONE-DIMENSIONAL CONSOLIDATION TEST AND THE SUCTION TEST.

effective pressure throughout equal to P_1 corresponding to a void ratio e_1, (or w_1, since the sample is saturated). The total stress at this time is equal to the effective stress.

which can be assumed equal to P_1 and a corresponding void ratio, e_1. (This statement is made on the assumption that the equilibrium points of consolidation are the same in both tests). However, the total stress is equal to zero while the pore water stress is equal to P_1 but negative in sign.

FIGURE 5b. - At the instant after the application of a pressure

At the instant after an increment of pressure is applied, the total stress on the soil is P_2. However, the effective pressure is P_1, and P_2 does not become completely effective until the void ratio decreases to e_2. There is an hydrodynamic lag which prevents the new pressure from becoming immediately effective. At an instant after the application of P_2, the change in pressure is carried by the water in the voids. The pressure thrown onto the water is an excess hydrostatic pressure and can be designated by u.

The theory which accompanies the consolidation process in a suction test, as explained in terms of neutral and effective stresses could not be found in literature. For this reason the following explanation has been postulated by the author. At the instant after an increment of pressure, all stresses in the soil mass remain as they were prior to the pressure application. The effective stress is P_1, the neutral stress is $-P_1$ and the total stress is equal to zero. However, as consolidation commences due to the applied hydraulic gradient,

At the instant after the load is applied the excess hydrostatic pressure at the surface of the sample is zero but a short distance inside the sample an excess hydrostatic pressure exists.	drainage results and the effective stress increases. The hydrodynamic lag which prevents P_2 from becoming immediately effective is due to the permeability of the soil. As the effective pressure increases, the tension in the pore water increases a corresponding amount. Therefore, the total stress remains at zero throughout the consolidation process. It should be noted that water flows due to a hydrostatic pressure similar in magnitude to that of the one-dimensional test. As drainage occurs the effective stress is built up at the point of drainage and slowly proceeds upward throughout the sample.

FIGURE 5c. - After partial consolidation

Gradually, the void ratio decreases, the hydrostatic excess pressure decreases and the intergranular pressures increase.	Gradually the void ratio decreases, the effective stress increases and the pore water tension increases. The isochrones of water stress are similar to those in the one-dimensional consolidation test.

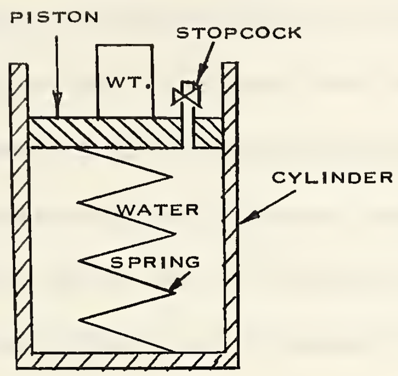
FIGURE 5d. - After complete consolidation

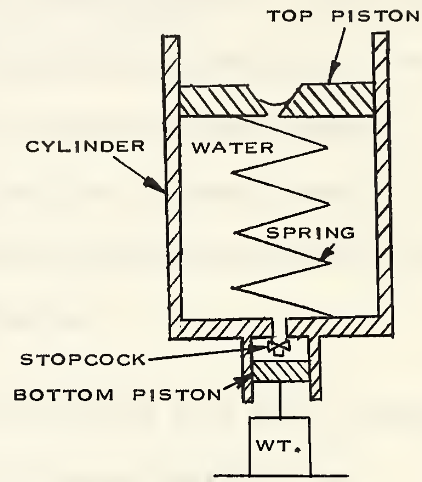
When hydrostatic excess pressure is equal to zero, the sample is consolidated under the pressure P_2.	When the pore water tension is equal to P_2, the effective stress is also equal to P_2. This negative pore water stress is called the 'soil suction'. The major difference between the mechanics of water egress in the two types of tests is that in the suction test the total stress remains zero throughout the consolidation process and there is simply a transfer of stress from the water phase to the soil structure resulting in an increase in effective stress.

The process of consolidation is easier to visualize if an analogy is developed. The mechanics involved in one-dimensional consolidation is often presented by a piston and spring analogy and a similar analogy for the suction consolidation process is postulated.

FIGURE 6. - Piston and Spring Analogy for One-Dimensional Consolidation and Suction Tests

ONE-DIMENSIONAL CONSOLIDATION ANALOGY	SUCTION PISTON AND SPRING ANALOGY





The spring and piston analogy for the suction test makes it easier to visualize the changes in stresses occurring during the consolidation process. A frictionless, tightly fitted piston is placed in the cylinder and in the chamber. The piston in the chamber has a hole in it which assimilates a pore in a soil mass. The stopcock at the bottom of the chamber is initially closed to prevent the escape of water and a load, P, is placed on the pan connected to the bottom piston. At the instant after the stopcock is opened, water starts to move from the chamber into the cylinder and as both pistons sink the load is taken up by the spring. The length of time required for the spring to take up the applied load depends upon the rate at which water escapes through the stopcock. When the pistons stop moving, the load on the spring is equal to P, the load in the water phase.

3:5 Terminology and Mathematical Relationships For The Suction Test

The suction test has been used to a limited extent in engineering fields and the data derived has never been assigned terms and mathematical relationships. In order to more intelligently discuss the results, the author takes the liberty to define several terms. It is felt that the pF-scale developed by Scofield for agricultural workers, is not convenient for engineering purposes and has in part been the cause of confusion among engineers regarding the suction test (Penner, 1961). Values of pF can be converted to other pressure scales and the units used in this thesis are kilograms per square centimeter.

The results from suction test can be plotted on a water content versus log soil suction plot in which case the curves bear the same characteristic shape as those of the one-dimensional consolidation test. Due to the similarity of processes involved and results obtained, the terms used to describe the conventional consolidation process will be applied to their respective processes in the suction test. The term "virgin compression branch" refers to the unique line on a water content versus log soil suction plot which describes the consolidation behavior of a soil subjected to a pressure in excess of any pressure previously applied to the soil mass. If a soil is consolidated in a suction test and the tension in the water phase is reduced, the resulting moisture contents lie on the "rebound or swell curve ". An increase in the tension of water would consolidate the soil mass on the "recompression curve".

It appears that for a saturated soil system, the mathematical relationships used to describe consolidation results in terms of effective

pressure and void ratio may be applied to the suction results where the respective terms "soil suction" and "water content" are used. The above transfer of definitions from the one-dimensional consolidation test to the suction test does not mean that both results are necessarily the same but rather that both are consolidation processes which may be explained in similar terms. A similar situation occurring in soil mechanics which will help clarify this point lies in the comparison of isotropic and anisotropic consolidation. Both types of consolidation may be described as equal in terms of neutral and effective stresses but different in terms of their equilibrium void ratios.

CHAPTER IV

PROCEDURES FOR THE PREDICTION OF HEAVE

4:1 General

The literature review revealed that two main analyses have been developed for the prediction of the total amount of heave which may occur to a building or other similar structure. One analysis was developed by Croney et al (1952) and is based on the results of a suction test and a shrinkage test. The other analysis developed by Jennings (1957) is based on the results of a "Double Oedometer Test".* The above analyses can be divided into two main parts; first, a method to show the initial conditions of a soil prior to construction and second, to predict the new equilibrium conditions after construction is completed.

4:2 Croney et al's Analysis

The Road Research Laboratory in Great Britain has used the soil suction test for several years to estimate the final equilibrium water conditions which may be expected beneath an asphalt or concrete covered road. The initial condition of the soil is measured in terms of a water profile. To determine the final soil conditions, Croney proposed an equilibrium suction profile which is negative and is a linear function of the distance above the water table. If a representative soil sample is taken from the field and a suction test performed on it, the results present the relationship between soil suction and water content. The soil suction values determined in the laboratory test are assumed to be equal

to the effective stresses in the soil sample and also equal to the final equilibrium effective stresses occurring in the field. The final effective stresses in the field may be calculated from a knowledge of the depth of water table. By using the suction test results, the final equilibrium water content can be estimated. A shrinkage test is also performed to determine the relationship between water content and specific bulk volume.*

The above analysis has been used to a considerable extent to predict heave beneath airfield runways and has proven to be very useful (Russam, 1962). However, there appears to have been some uncertainty and diversity regarding which soil suction versus water content plot should be used for the analysis and the method whereby it should be applied (Black et al, 1958; Capper and Cassie, 1961; Russam, 1962). Much of the confusion appears to have besulted from an inadequate understanding of the factors familar to engineer practice which affect the soil suction relationship. Although the analysis is only an approximation for the amount of heave, other research workers feel that Croney has taken a useful approach to the problem and that it should be further investigated (Williams, 1963; Cooling, 1960). They have suggested that the above analysis may be improved by using field measurements of the tension in the water phase to describe initial conditions. The approach initiated by Croney appears promising and further work on the analysis is recommended. A more detailed outline of the procedure for an estimation of total heave is found in Appendix B.

4:3 Jenning's Analysis

Jennings noted the uncertainty of the pore pressure profile

attaining the static equilibrium conditions proposed by Croney and introduced an empirical factor which would give a more realistic equilibrium condition. The factor ranged between the limits of zero and one, and reduces the equilibrium suction conditions used by Croney. However, it is difficult to determine the value for this empirical factor (Aitchison and Holmes, 1961).

Jennings developed a prediction of heave analysis based on information from two types of consolidation tests which he called the 'Double Oedometer Test'. The first sample is consolidated in accordance with the procedure normally used for the 'Free Swell'* test. This test is to assimilate the final equilibrium water content conditions after an impermeable covering is placed over the soil. It should be noted that Jennings used the free swell consolidation test for the same purpose as Croney used the suction test. The second sample is consolidated as a 'Natural Water Content'* test with no evaporation or excess water allowed to come in contact with the soil. This test is to assimilate field conditions where a load is applied to the soil which does not disrupt the moisture regime. In other words, this test describes the initial conditions of the soil mass. The amount of heave is predicted by determining the change in void ratio which occurs between the initial and final field conditions. A detailed outline of Jennings' analysis is contained in Appendix B.

There has been considerable controversy over the interpretation and application of the double oedometer test results (Jennings and Knight, 1957; Burland, 1962; Denesson et al, 1963). One point of contention has

been the manner in which Jennings plotted the test results. Both the free swell and natural water content consolidation test results are plotted to the same scale on the void ratio versus applied pressure plot. Burland (1962) showed that Jennings was plotting effective stresses from the free swell test on the same scale as the applied stresses from the natural water content test. Jennings found that the virgin compression branches of the consolidation curves for the two tests did not coincide and Burland explains the difference as the result of the manner in which the stresses are plotted.

Analysis for the prediction of heave by Jennings' method has consistently given higher values than those measured in the field. Burland (1962) explains that the natural water content consolidation test has been improperly applied and goes on to develop an analysis in terms of effective stresses which incorporates the rebound curve of a consolidation test. Estimations of heave based on this procedure correlate much better with actual field measurements. The analysis is also more economical since only one consolidation test is required. Due to the simple and practical nature of this analysis, it is suggested by the author that further investigation be performed on the application of Burland's analysis to soils in Western Canada.

CHAPTER V

SOIL AND TESTING PROGRAM

5:1 General

The purpose of this chapter is to describe the soil and testing equipment used for the laboratory investigation. The method of soil preparation and the testing program will also be briefly reviewed. Considerable time and effort was spent on the development of apparatus and workable procedures which would produce accurate results for research purposes. Since this information may be of benefit for further research, detailed descriptions pertaining to the various phases of this chapter are contained in the Appendix of this thesis.

5:2 Soil

The soil used for this testing program was obtained in the summer of 1963 from the basement excavation for the new Saskatchewan Government Telephone Building in Regina, Saskatchewan. Disturbed samples were taken from a depth of approximately fourteen feet below the original ground surface, that is, well below the zone of weathering. The soil which is geologically classed as a glacial lake sediment is often referred to as 'Regina Gumbo'.

Classification tests were performed in accordance with the procedures of the American Society for Testing and Materials and designated as Specific Gravity D854-52, Liquid Limit D423-54T, Plastic Limit D424-54T,

Shrinkage Limit D427-39 and Grain Size Analysis D422-54T. The mineralogical composition of the clay fraction was determined by the Alberta Research Council using X-ray diffraction techniques. Total exchange capacity and exchangeable cations were determined by the Soil Science Department at the University of Alberta. Results of the classification tests are summarized in TABLE 1. From these tests, the soil is classified as a highly plastic clay. The predominent clay mineral is montmorillonite and the exchangeable complex appears to be nearly saturated with adsorbed calcium and magnesium.

5:3 General Comments on Suction Test Apparatuses

There appeared to be no conventional apparatus found in soil mechanics laboratories in Canada which could be used for the measurement of the soil suction characteristics of a soil. Therefore, it was necessary to either develop suitable equipment or else obtain equipment from soil science or agricultural workers who have developed several methods for the measurement of soil suction (Richards, 1949).

A wide range of pressures are involved in the measurement of soil suction when a soil is dried from a high water content state to an oven-dried state. Therefore, several techniques must be employed to obtain the soil suction versus water content relationship over the total water content range. After an extensive literature review of methods used by other investigators, it was decided to use the following three techniques:

i) Pressure Plate Extractor

ii) Pressure Membrane Extractor

iii) Vacuum Desiccator

TABLE I

SUMMARY OF CLASSIFICATION TESTS ON REGINA CLAY

TEST	RESULT
Specific Gravity	2.83
Atterberg Limits	
Liquid Limit	75.5
Plastic Limit	24.9
Shrinkage Limit	13.1
Plasticity Index	50.6
Grain Size Distribution*	
% Sand Sizes	8
% Silt Sizes	41
% Clay Sizes	51
Mineralogical Composition of Material less than 2 microns**	
Montmorillonite	77
Illite	15
Kaolinite	8
Exchange Capacity*** (milliequivalents per 100 grams dry weight of soil).	31.7
Exchangeable Cations	
Magnesium	15.3
Calcium	54.4
Potassium	0.59
Sodium	1.77

* M.I.T. Grain Sixe Scale

** X-Ray Analysis performed by Alberta Research Council

*** Exchange capacity analyses were performed by the Soil Science Department, University of Alberta.

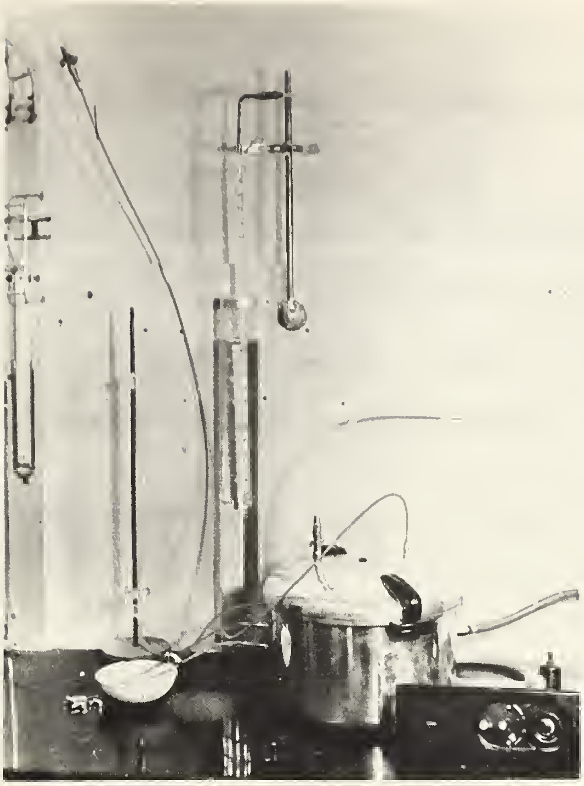
These methods are briefly outlined in the following paragraphs while a detailed discussion of these and other measuring techniques is found in Appendix C.

5:4 Pressure Plate Extractor

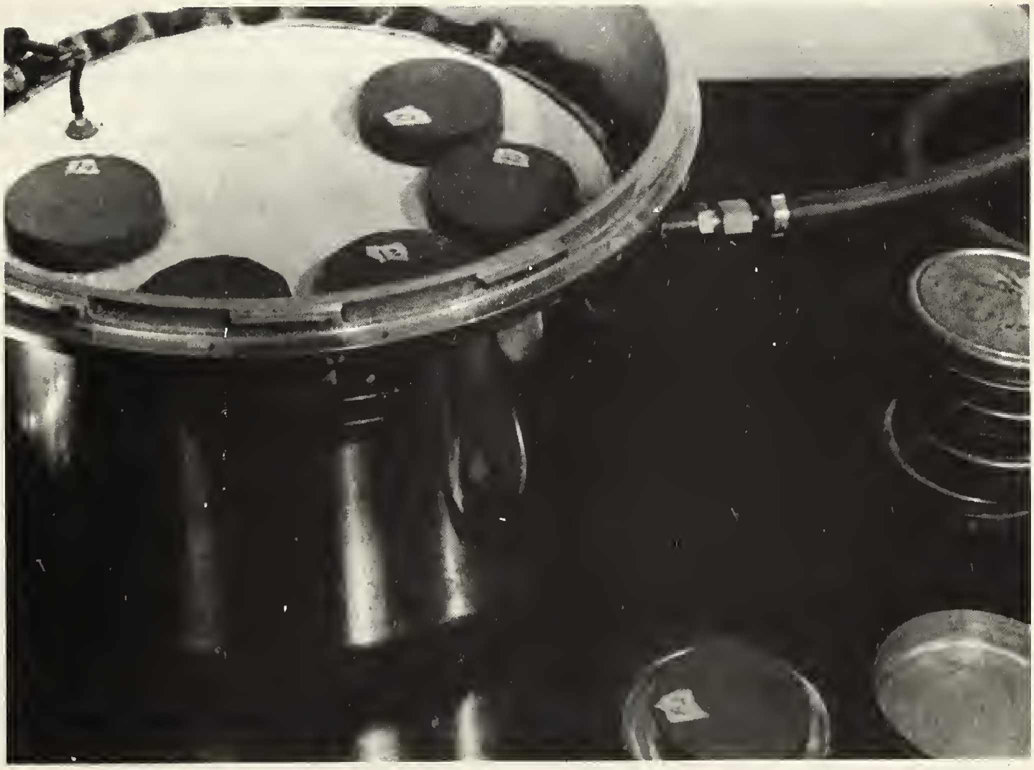
The pressure plate extractor was obtained from the Agricultural Engineering Department of the University of Saskatchewan, Saskatoon. It consists of three 10-inch ceramic discs in a 13 quart pressure cooker. (See PLATE 1). The operative range of the pressure plate depends upon the pressure difference which can be maintained across the saturated ceramic plate before it allows the passage of air. Therefore, the maximum pressure applied is a function of the largest pore size in the ceramic plate. The pressure plate extractor allows a pressure difference of one kilogram per square centimeter which was felt to be satisfactory for the low pressure range.

Very similar to the pressure plate method is the suction plate equipment which has been used by several investigators (Croney et al, 1961; Richards, 1949). The only difference in this equipment is the method by which pressure is applied to the ceramic disc. In the pressure plate extractor a positive pressure is applied through a pressure regulator to the top of a saturated porous plate while in the suction apparatus the porous plate is kept at atmospheric pressure and the water in contact with the bottom of the plate is placedin tension through a vacuum regulator. Both methods have been proven to give essentially the same answers (Penner, 1959).

Several modifications were made on the apparatus in an attempt



[A] PRESSURE PLATE EXTRACTOR



[B] SAMPLES ON POROUS DISC IN PRESSURE CHAMBER

PLATE I

to increase the accuracy of the results:

i) the pressure release valve was sealed off because it would not stay closed at low pressures.

ii) a water head regulator was used to keep low pressures constant and accurately measure the pressure applied to the pressure chamber.

iii) a two-stage Conoflow regulator from a Bristol recorder with a sensitivity of ± 0.2 inches of water (± 0.0005 kg/cm^2) was used.

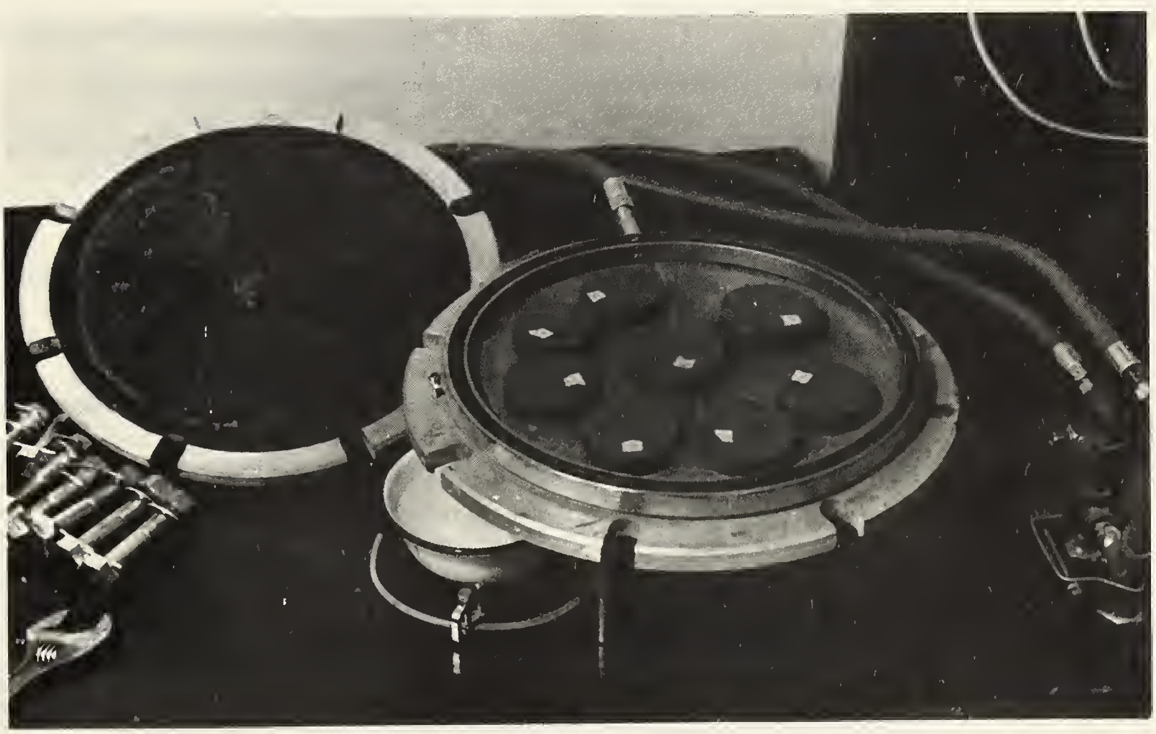
Details of the assembly and its performance are given in Appendix C.

5:5 Pressure Membrane Extractor

The pressure membrane extractor was also borrowed from the Agricultural Engineering Department of the University of Saskatchewan. (See PLATE 2). It extends the range of the porous plate since it is suitable for pressures from 1/2 to 15 kg/cm^2. The main difference between this apparatus and the pressure plate extractor is a cellulose membrane which is stretched over a fine screen. The cellulose membrane has pores which are sufficiently small to withstand the passage of air up to a differential pressure of 15 kg/cm^2.

A mercury differential regulator is connected in series with the pressure supply line in order to exert pressure on the top of the sample which is greater than the pressure around the sides of the sample. The purpose of the regulator is to ensure good contact between the soil sample and the cellulose membrane. However, the initially used differential pressure of 4 psi deformed the samples and for this reason it was reduced to 2 psi. Aluminum plates were also placed over the top of the samples

[A] PRESSURE MEMBRANE EXTRACTOR



[B] SAMPLES ON MEMBRANE IN PRESSURE CHAMBER

PLATE 2

to prevent the corners from becoming rounded. The pressure source was a nitrogen tank under a pressure of 2200 psi. The pressure applied to the pressure chamber was initially regulated by a standard No. 511 Hoke regulator but it was not sensitive enough and was later replaced by a two-stage regulator connected in series with the pressure supply. Further details on this assembly are given in Appendix C.

5:6 Vacuum Desiccator

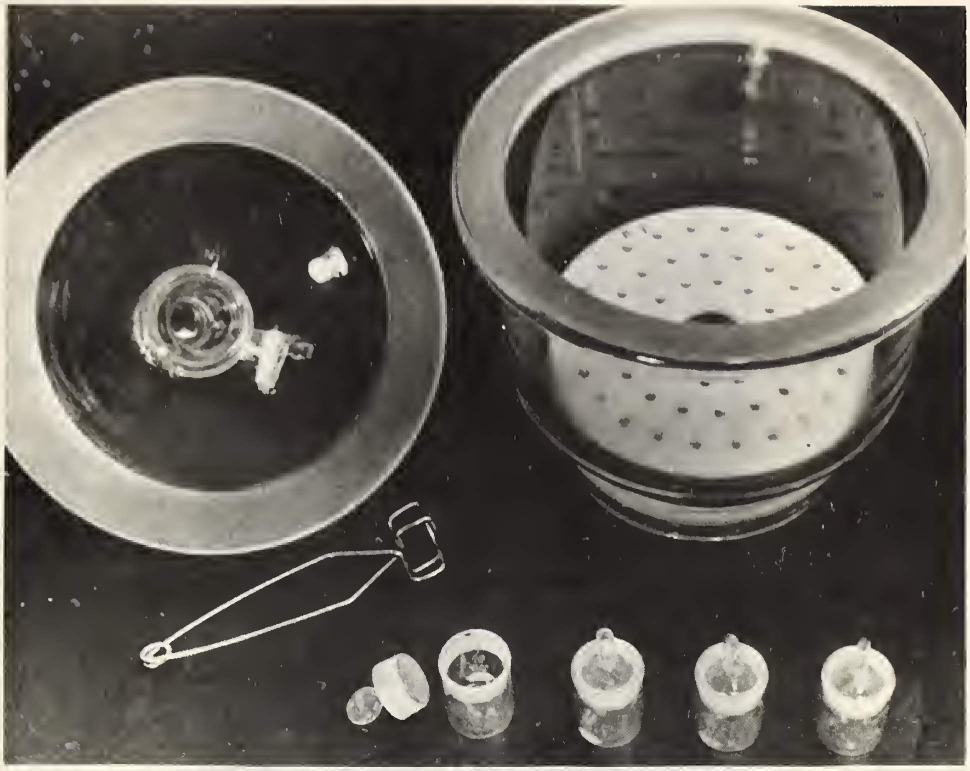
The vapor pressure technique was used to establish equilibrium water contents corresponding to high soil suctions. Vacuum desiccators with various salt slurries placed in the botton provided atmospheres of constant relative humidity in the desiccator. Small glass soil sample containers with ground glass lids ensured no uptake or release of moisture from the sample during handling. (See PLATE 3).

5:7 New Pressure Plate Apparatus

The pressure plate extractor has several disadvantages which limit its usefulness for research work in the engineering field. Hence, it was desirable to develop a more versatile apparatus. (See PLATE 4). The main purpose of the new pressure plate apparatus is to aid in further research which may be carried out in this field. The equipment was built and several tests performed which checked its reliability. In principle its operation is similar to that of the pressure plate extractor.

Advantages incorporated in the new equipment are as follows:

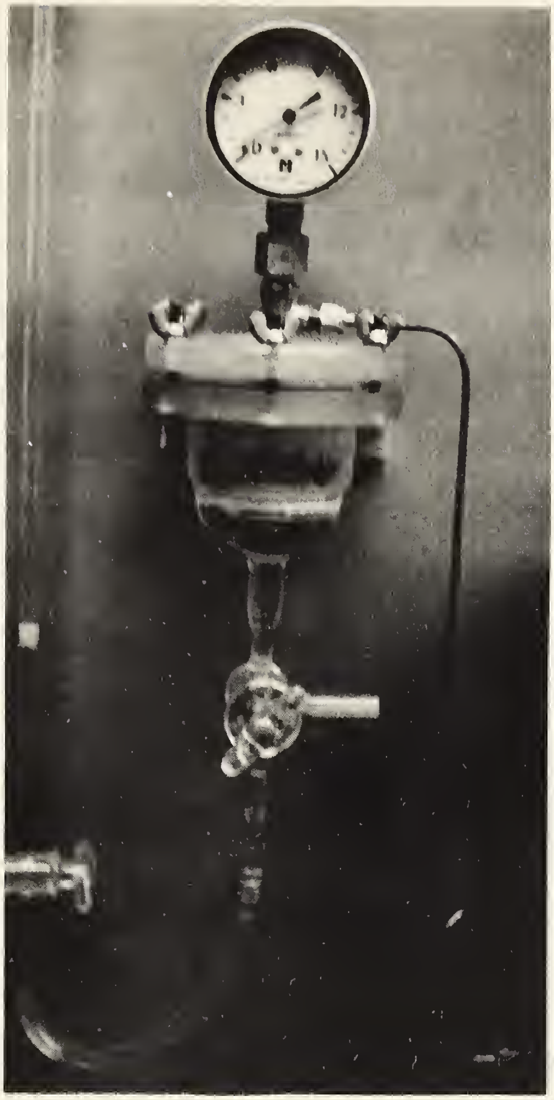
i) It is not necessary to remove the sample from the porous plate after each pressure increment to measure its wet weight since the change in water content is determined by measuring the volume of water re-



[A] VACUUM DESICCATOR WITH SOIL CONTAINERS AND HOLDER

[B] SAMPLES IN SOIL CONTAINERS

PLATE 3



NEW PRESSURE PLATE APPARATUS

BURET ON THE LEFT MEASURES VOLUME CHANGE

PRESSURE CHAMBER IN WHICH SOIL SAMPLE IS PLACED IS IMMEDIATELY BELOW THE PRESSURE GAUGE IN THE CENTRE OF THE PICTURE

COPPER LINE ON THE RIGHT OF THE PRESSURE CHAMBER LEADS TO SENSITIVE PRESSURE REGULATOR

PLATE 4

moved from the sample.

ii) The chamber pressure does not need to be reduced to atmospheric conditions between increments.

iii) The rate of consolidation can be determined since the rate of water removal from the soil can be measured in a buret.

iv) The procedure lends itself to the establishment of both the wetting and drying soil suction versus water content curves.

One limitation of the apparatus results from not being able to measure the total volume of the specimen. The total volume of the soil sample was not an important factor in this testing program since the samples were always near 100 per cent saturation. However, if further research is carried out using partially saturated soils it would be beneficial to incorporate a volume measuring device into the design. Details on the apparatus are found in Appendix C.

5:8 One-Dimensional Consolidation Apparatus

Consolidation tests were performed on the Wykem-Farrance bench model consolidometers at the University of Alberta. They are equipped with stainless steel, fixed rings and are listed as having a multiplication factor of 11:1. Since the consolidation results are to be compared with the suction results, it is essential that mechancial errors and inaccuracies be either eliminated or taken into account. In other words, when comparing results on an absolute basis, correction should be applied for mechanical inaccuracies.

The multiplication factors were investigated in order to find how accurate the listed values were. They were found to deviate approxi-

mately $\pm 1\frac{1}{2}$ per cent from the stated 11:1 ratio. Details are found in Appendix D.

Generally, the compressibility of the apparatus is not taken into account for consolidation testing but a check was made to determine its significance (Matlock and Dawson, 1951). Since filter paper was used above and below the sample, its compressibility was also measured. The total compressibility was found to affect the compressive index by as much as 9 per cent. Details of the investigation are contained in Appendix D.

Friction of the soil against the sides of the steel consolidation rings is also of significance but is very difficult to measure. Therefore, corrections are based on work done by other investigators (Lambe, 1951; Leonards, 1961).

5:9 General Comments on Sample Preparation

Similar to any experimental laboratory study, it was desirable to use procedures which would eliminate all variables other than those under investigation. Since the main interest was in the basic relationships between the neutral and effective stress of the suction and one-dimensional consolidation tests, such secondary factors as soil structure and physico-chemical phenomena should be kept constant.

Disturbed field samples were initially air-dried, ground to pass a No. 40 sieve and thoroughly mixed. The soil for all tests was slurried at a water content of approximately 100 per cent (well above the liquid limit) and consolidated in accordance with the outlined testing program. Thus, soil structure and physico-chemical relationships should be relatively

uniform for all specimens.

5:10 Suction Test Sample Preparation and Test Procedures

The specimens for both the pressure plate and the pressure membrane extractor were prepared in a similar manner. They were consolidated from a slurry to various initial densities in one-dimensional consolidometers. Special 2-inch high by 2½-inch diameter lucite rings were used on the PFRA design consolidating machines at the University of Saskatchewan Soils Laboratory. Filter paper was placed both at the top and bottom of the specimen next to the porous stones. A circular teflon-coated ring was placed on top of the porous stone to keep the applied load vertical. This prevented tilting and binding of the stones against the lucite ring. The pressure was increased slowly to prevent soil from squeezing out around the porous stones. After the desired pressure was reached, consolidation was allowed for at least 24 hours. Then they were rebounded under a pressure of 0.003 kg/cm^2 for about 48 hours. Better control of the preconsolidation load at low pressures (less than ¼ kg/cm^2) was obtained by applying a direct load to the sample rather than using the multiplying lever system of the consolidation apparatus.

The fine, porous stones of the pressure plate extractor were saturated by forcing desired water through them before samples were placed on them. The rebounded samples were then removed from the lucite rings and placed on the porous plate. No support was placed around the samples as is often done for less cohesive material. At least 24 hours was allowed at each pressure for equilibrium conditions to be established. Before releasing the air pressure to remove the samples at each equilibrium

condition, a pinch clamp was placed on the outflow tube of the ceramic plate. This prevents backflow of water to the specimen after the pressure is released. Samples were quickly transferred to moisture tins to avoid a change in water content. Measurements were made of their wet weight and volume. Total volume was measured by mercury immersion. Careful handling of the samples during all phases of the procedure is essential for accurate results. The above procedure was repeated at increased pressures. After the 1 kg/cm^2 pressure in the pressure plate extractor, volume and water content measurements were made on several samples as they were slowly dried.

The test procedure for the pressure membrane extractor is similar to that of the pressure plate extractor. However, the apparatus is more complicated to operate and extreme care must be exercised when working with high air pressures. Detailed outlines of procedures for both apparatuses along with a discussion of each is found in Appendix E.

The vacuum desiccator tests for high soil suctions were performed on approximately two-gram samples. The soil was initially either air-dried, oven-dried, or at a water content slightly above the estimated equilibrium conditions. Samples were placed in small pyrex containers and placed in a constant relative humidity desiccator. Constant humidity conditions were supplied by placing salt slurries in the bottom of the desiccator. The desiccators were evacuated and placed in a room of relatively constant temperature for three weeks, after which time each sample plus container was weighed to the nearest ten thousandth of a gram. They were returned to the desiccator and weighed each succeeding week until their

change in weight was less than one thousandth of a gram. No measurement of the sample volume was possible. Details of the procedure and the salt solutions used are outlined in Appendix E.

5:11 Consolidation Test Sample Preparation and Test Procedure

One-dimensional consolidation tests were performed in accordance with the procedure outlined by Burmister (1959) in the ASTM Procedures for Testing Soils, with the following exceptions. Soil was initially slurried at 100 per cent water content and poured into the consolidation ring. The degree of saturation was assumed to remain constant throughout the test, therefore making the change in volume registered on the dial gauge equal to the change in water content. A number 2 Whatman filter paper was placed both above and below the sample and several of the test results were corrected to compensate for the compressibility of the filter paper. Side friction in the consolidation rings was also considered in several consolidation test results. The desired end result was consolidation characteristics of the soil with the effects of procedure and apparatus having been accounted for. Details on the evaluation of compressibility of apparatus and filter paper and the effect of side friction are found in Appendix D.

5:12 Testing Program

The testing program can be divided into two parts in view of the objective of the thesis. The first part involves the measurement of the soil suction versus water content and specific bulk volume relationships for the soil and the second part involves the comparison of these results to those obtained from one-dimensional consolidation tests. To establish

the first objective, tests were performed on the pressure plate extractor, pressure membrane extractor and the vacuum desiccator. Samples for the first two apparatuses were prepared in duplicate at preconsolidation pressures varying on a logarithmic scale from 0 to 4 kg/cm^2. Determinations of both water content and specific bulk volume were made at each equilibrium pressure for all samples. Only the drying curve was determined in these tests since the equipment did not lend itself to the establishment of the wetting curve. In several cases, the samples removed after the final pressure in the pressure plate extractor were slowly dried while water content and volume measurements were taken. Volume and water content measurements were also taken on several samples dried by evaporation from a slurried state in order to check the drying behavior by evaporation with that of consolidation process in the suction apparatuses. Vacuum desiccator tests at four relative humidities were carried out to establish equilibrium water contents for high soil suctions. Samples were prepared to give both the adsorption and desorption curve by preparing samples below and above the estimated equilibrium water content. Two tests were performed on the new pressure plate apparatus to measure the time versus volume change characteristics occurring in the suction test.

To fulfill the second objective, several one-dimensional consolidation tests were performed on slurried soil. Each sample was consolidated to a pressure similar to that of the suction test samples, rebounded under approximately 0.005 kg/cm^2 and then reconsolidated to about 10 kg/cm^2. Details of the testing programs are outlined in Appendix F.

CHAPTER VI

PRESENTATION OF TEST RESULTS

6:1 General

This chapter presents the observed data from the laboratory testing program. The test results are presented in a graphical form in the chapter and the interpretation of the results is presented in the following chapter. A complete summary of all test results, as well as example data sheets, is contained in Appendix G.

6:2 Test Results from the Pressure Plate and Pressure Membrane Extractors

The main plots used to show the equilibrium conditions obtained during the suction tests and one-dimensional consolidation tests are the water content versus log of soil suction (w-log p" curve) for the suction test, and water content versus log effective pressure (w-log σ' curve) for the one-dimensional consolidation test. The suction test data is presented first in this chapter. FIGURE 7 shows a summary of the water content versus logarithm of soil suction relationship for all suction tests performed on both the pressure plate and pressure membrane extractors. It should be noted that these pressures are negative, relative to the surrounding environment. The best-fit lines through the data possess a shape similar to the characteristic e-log P consolidation curves. However the break in slope of the recompression branch does not appear to be as pronounced as in the one-dimensional consolidation test. Scatter of equilibrium water content values on the virgin compression branch of the

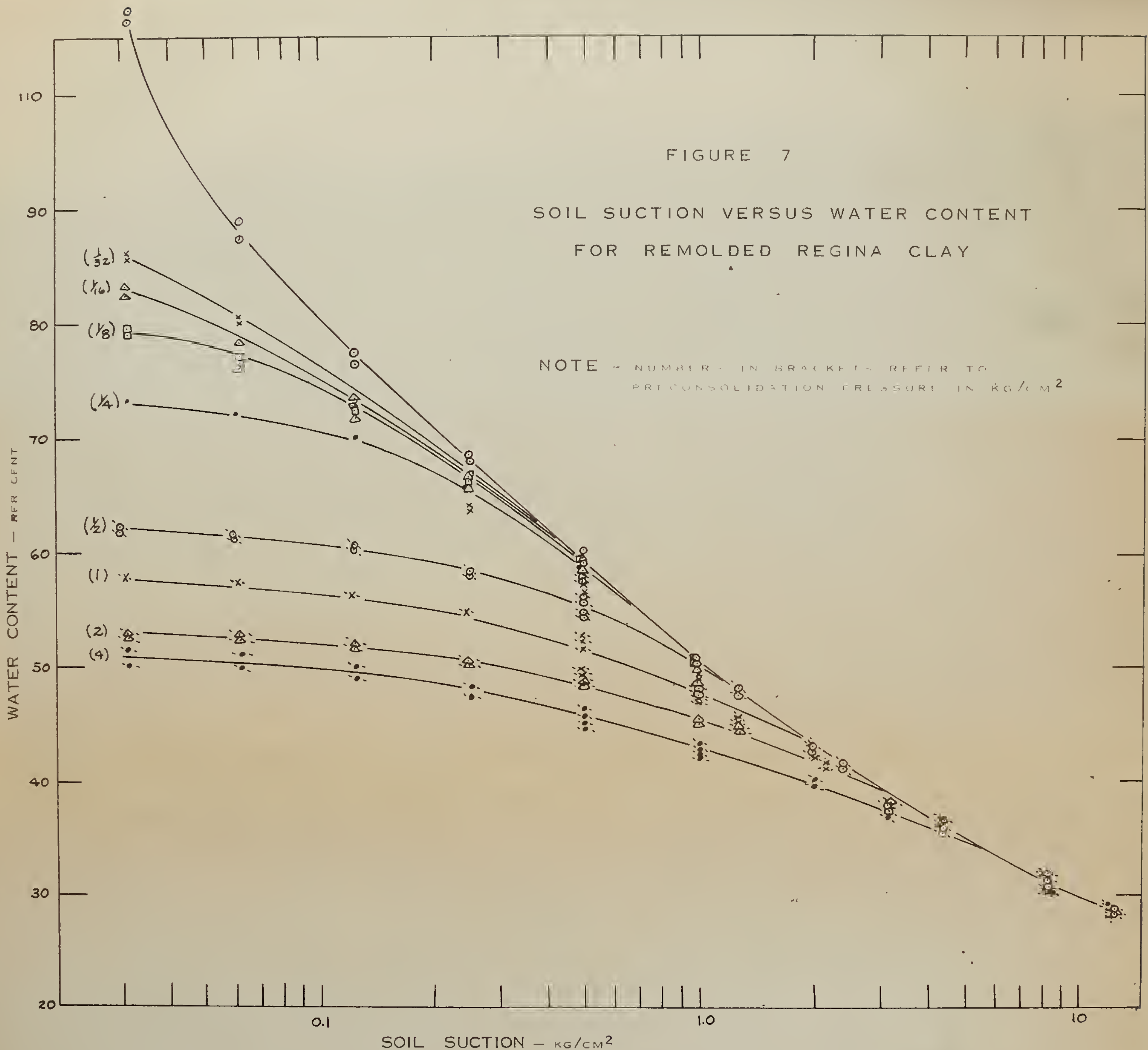


FIGURE 7

SOIL SUCTION VERSUS WATER CONTENT FOR REMOLDED REGINA CLAY

NOTE – NUMBERS IN BRACKETS REFER TO PRECONSOLIDATION PRESSURE IN KG/CM^2

suction test curve is approximately $\pm$ 1.5% in terms of water content. In order that the above data may be compared to that found in literature, the data from FIGURE 7, along with the vacuum desiccator results which will be presented later, have been replotted in the standard manner used by agricultural and soil science workers (FIGURE 8). The curve appears to be very similar to results obtained by Croney et al (1958) for a highly plastic clay.

The pressure plate extractor results extend over the range from 0.031 to 1.0 kilograms per square centimeter and a typical set of test results are shown on FIGURE 9. Typical results from the pressure membrane extractor are shown on FIGURE 10 and cover the range of soil suction from 0.5 to 12 kg/cm^2. Results from both apparatus give a fairly straight line relationship at suction values in excess of the preconsolidation pressure on the semi-log plot of water content versus soil suction. Included on this plot are the variation of specific bulk volume and the degree of saturation with soil suction. It should be noted that both specific bulk volume and water content are referenced to the same base, namely the dry weight of soil solids, and thus can be plotted to the same scale. By using this method of plotting, the parallelism of the lines becomes a measure of the change in degree of saturation.

FIGURES 11 and 12 show the relationship between specific bulk volume and water content as samples were dried first in the pressure plate extractor and later by evaporation. Results on all samples were similar hence only four sets of results are shown and the remainder of the data is summarized in Appendix G. The plot of specific bulk volume versus

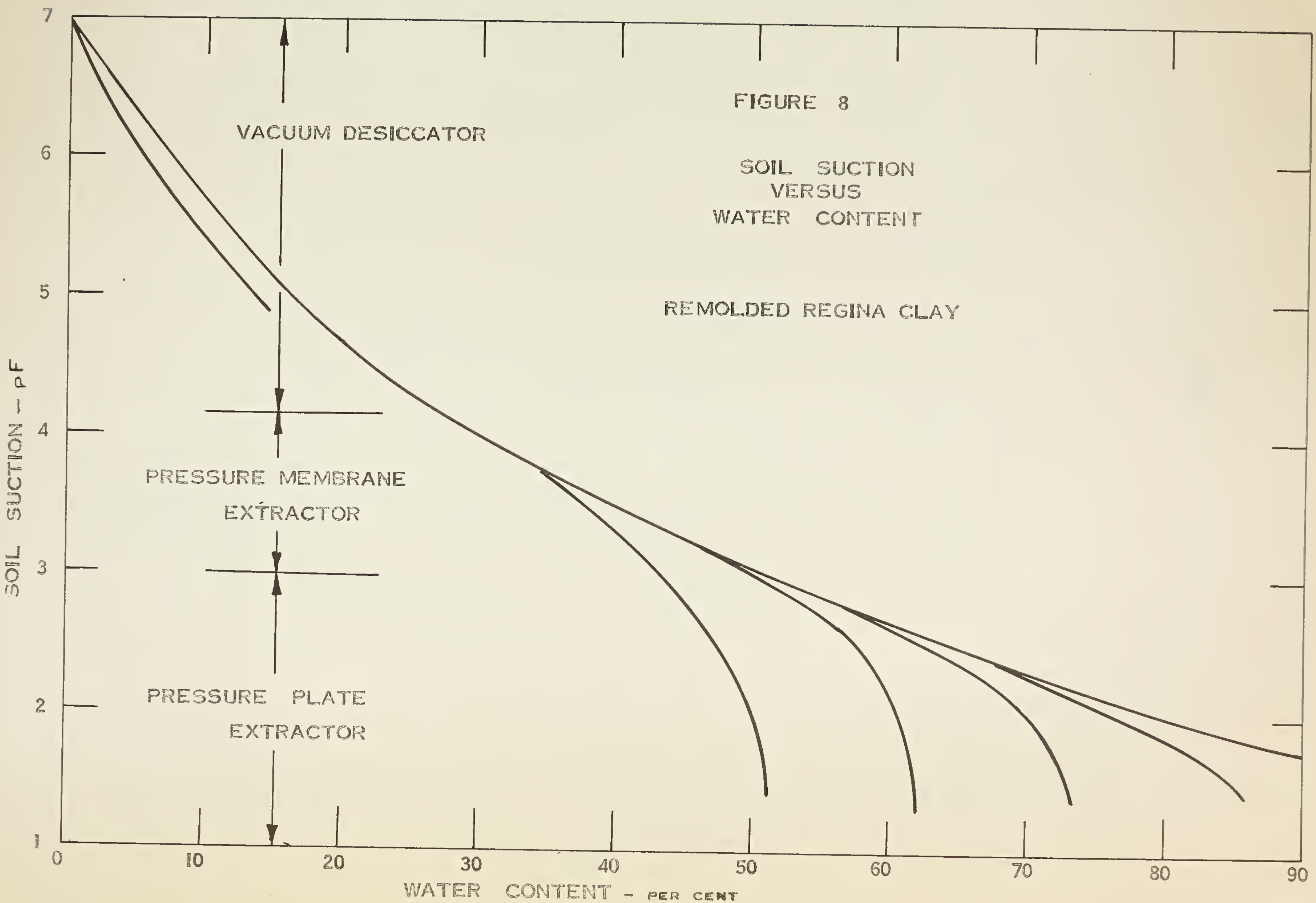


FIGURE 8

SOIL SUCTION VERSUS WATER CONTENT

REMOLDED REGINA CLAY

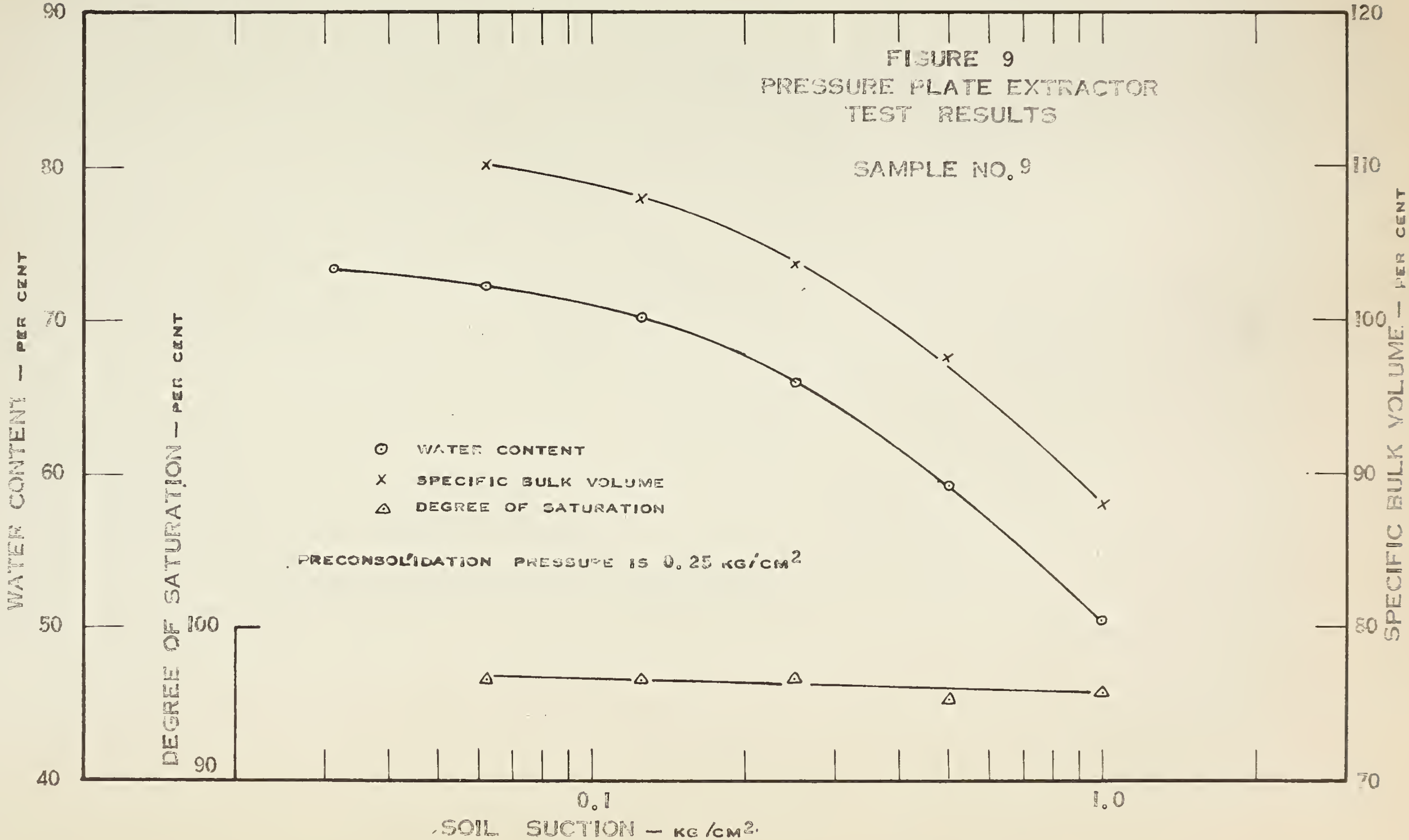


FIGURE 9
PRESSURE PLATE EXTRACTOR
TEST RESULTS

SAMPLE NO. 9

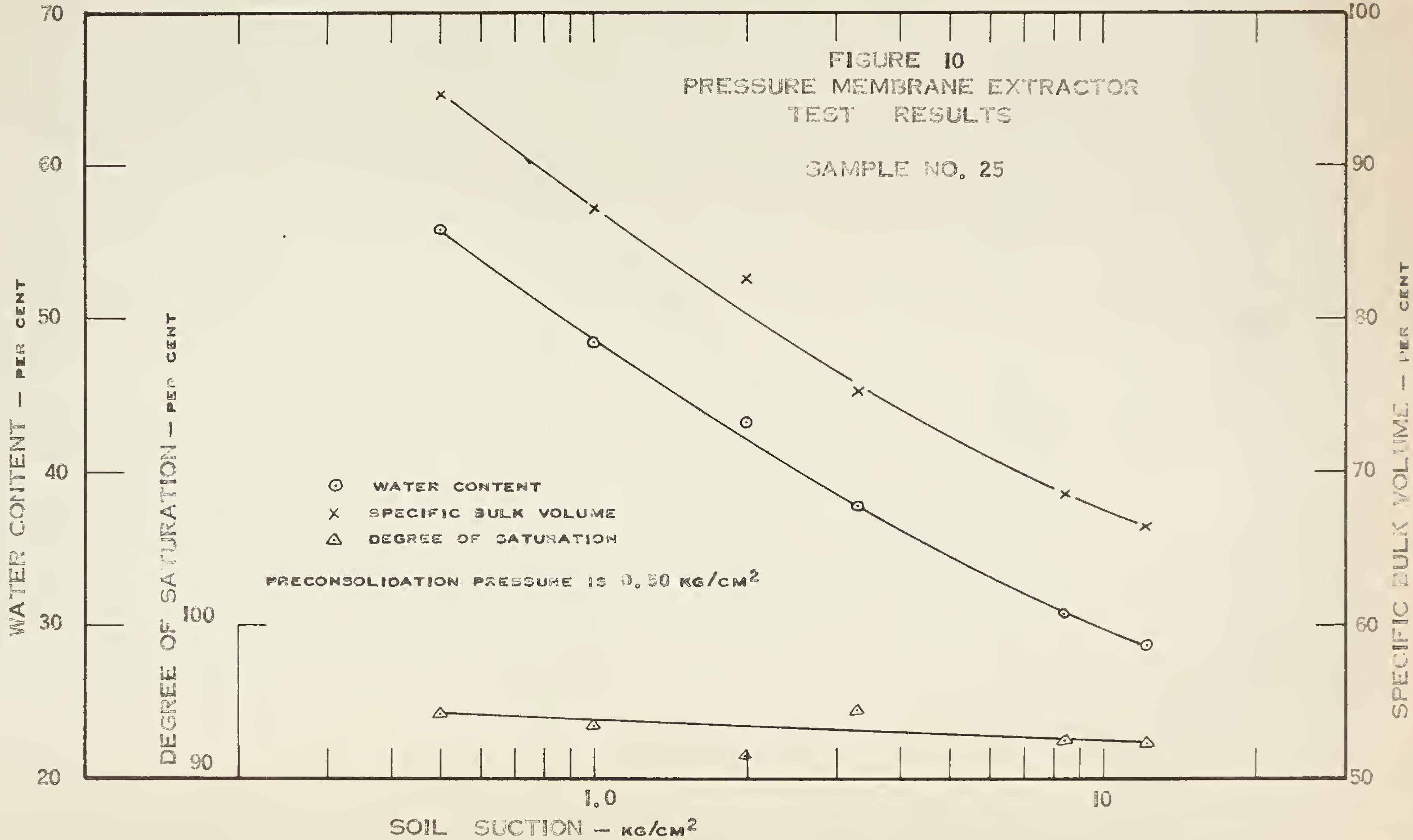


FIGURE 10
PRESSURE MEMBRANE EXTRACTOR
TEST RESULTS

SAMPLE NO. 25

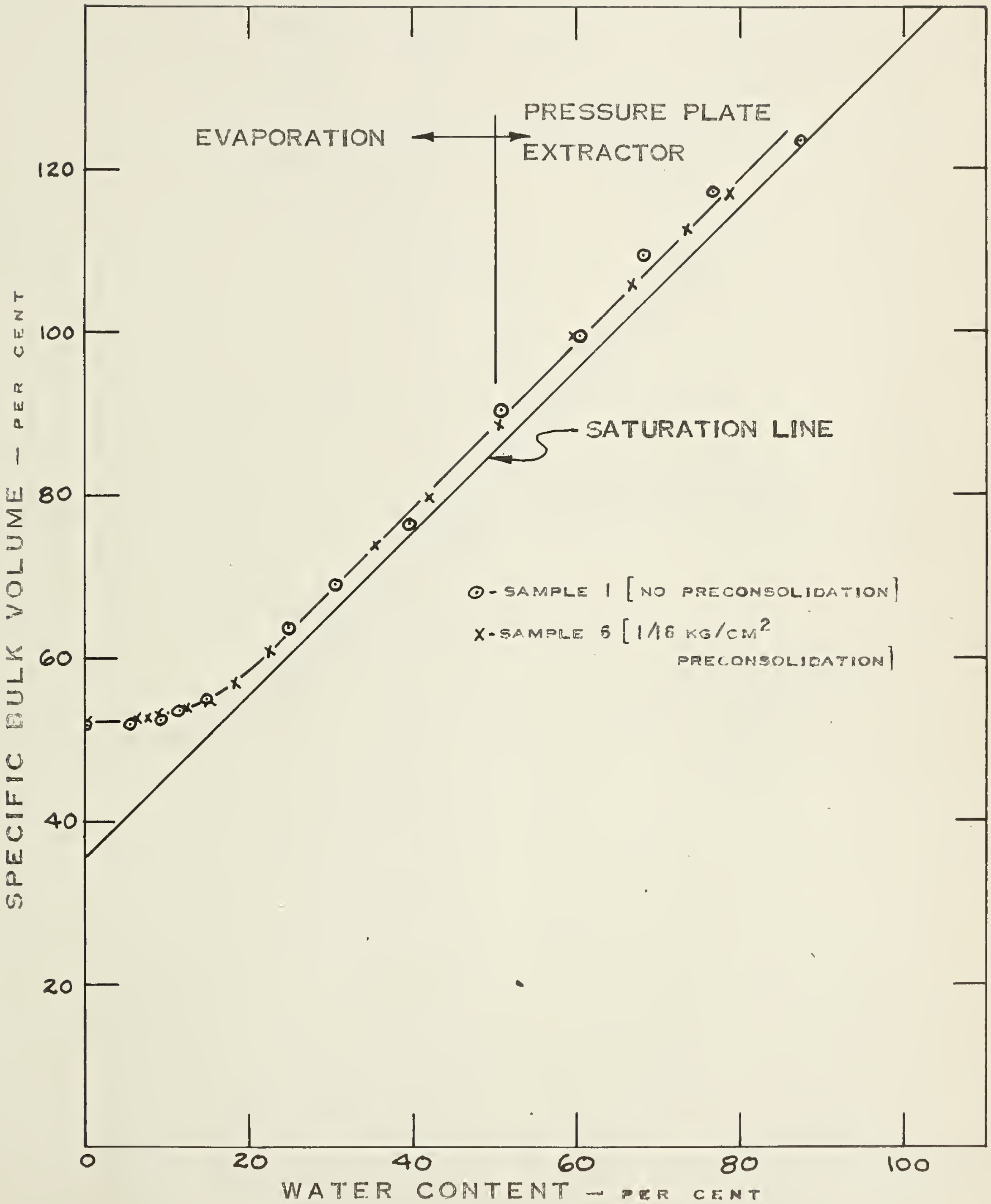


FIGURE II SPECIFIC BULK VOLUME VERSUS WATER CONTENT

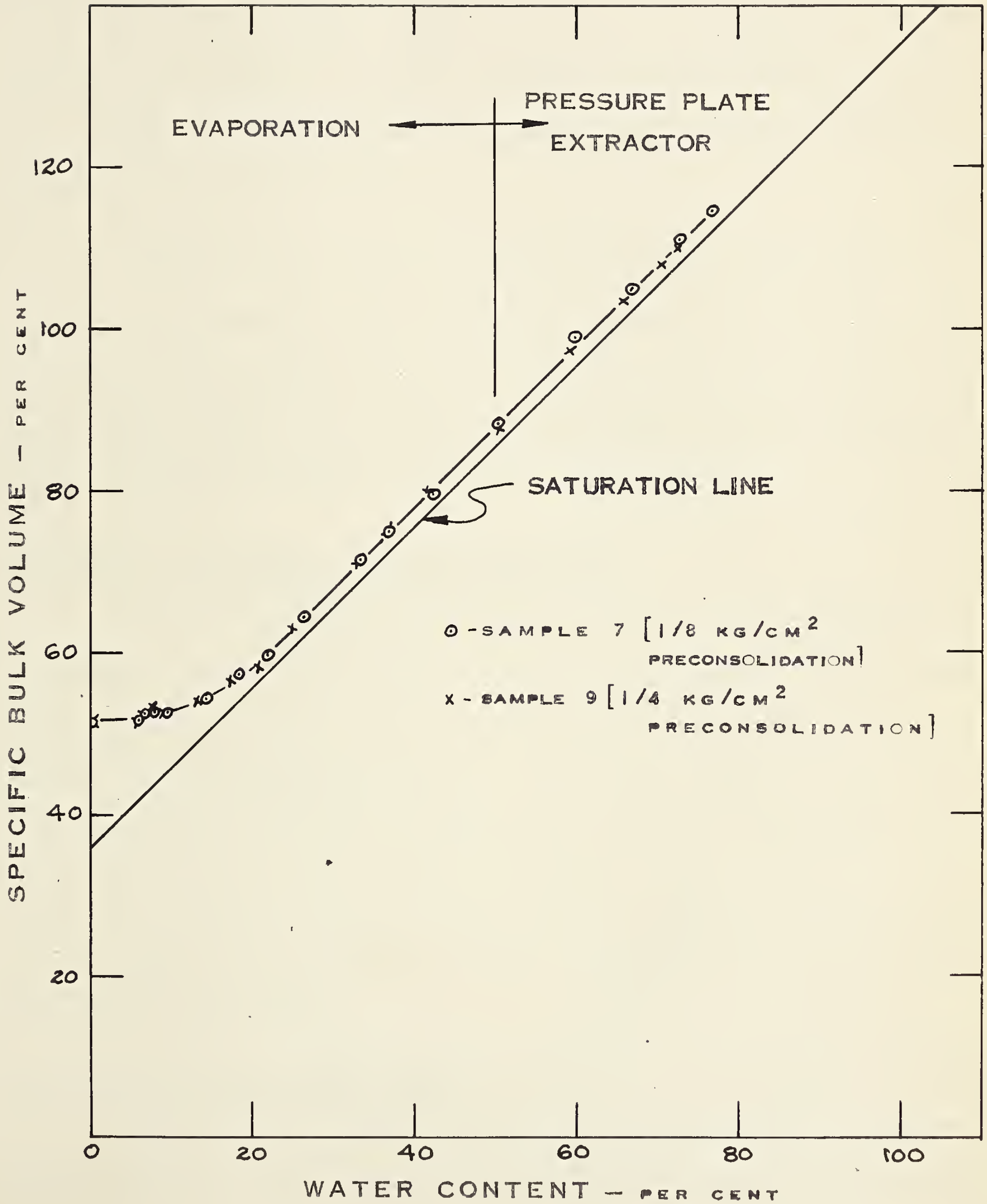


FIGURE 12 SPECIFIC BULK VOLUME VERSUS WATER CONTENT

water content shows a straight line relationship at approximately 45 degrees for water contents in excess of 20 per cent. This indicates that the degree of saturation remains relatively constant.. This is confirmed by FIGURES 13 and 14 which show the degree of saturation versus water content for the above mentioned samples. The plots show that only a slight decrease in the degree of saturation occurs during the suction test and upon subsequent drying by evaporation until a water content of approimately 25 per cent is reached.

The degree of saturation of the suction test sample was calculated to be between 90 and 100 per cent and therefore all samples may be considered essentially saturated. For this reason no correlation was made between specific bulk volume and soil suction since it would merely duplicate the water content versus soil suction plots.

6:3 Results from Samples Dried by Evaporation

Plots of specific bulk volume versus water content and degree of saturation versus water content for initially slurried samples which were dried by evaporation from a water content of approximately 100 per cent are shown on FIGURES 15 and 16. Due to the scatter in the results, it is difficult to accurately compare the two methods of drying but the degree of saturation at the end of the pressure plate and pressure membrane suction tests appears to be almost 2 per cent lower than the samples evaporated from a slurry.

6:4 Vacuum Desiccator Test Results

The vacuum desiccator test results shown in FIGURE 17 extends the water content versus soil suction relationship to soil suction greater

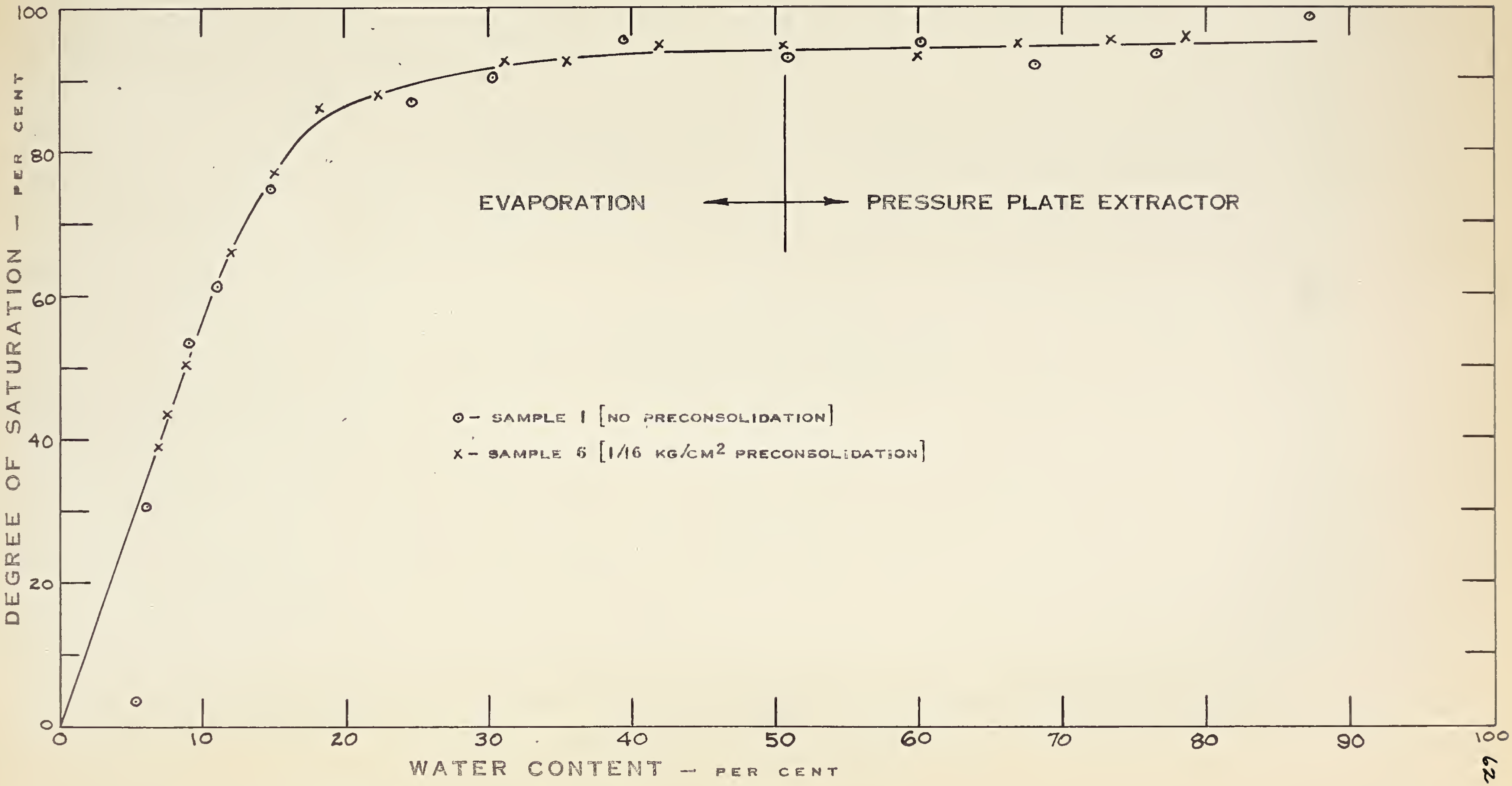


FIGURE 13 DEGREE OF SATURATION VERSUS WATER CONTENT

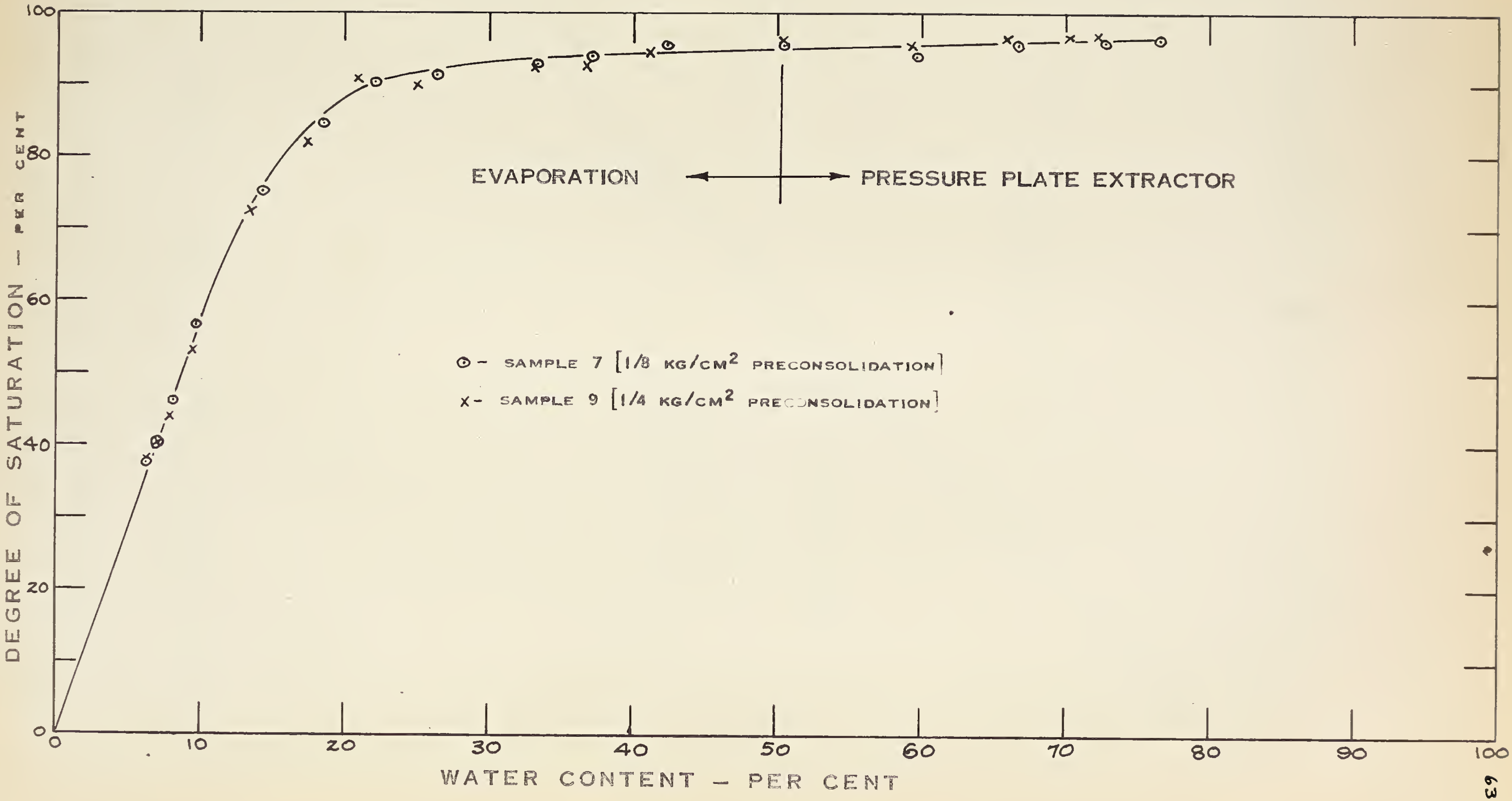


FIGURE 14 DEGREE OF SATURATION VERSUS WATER CONTENT

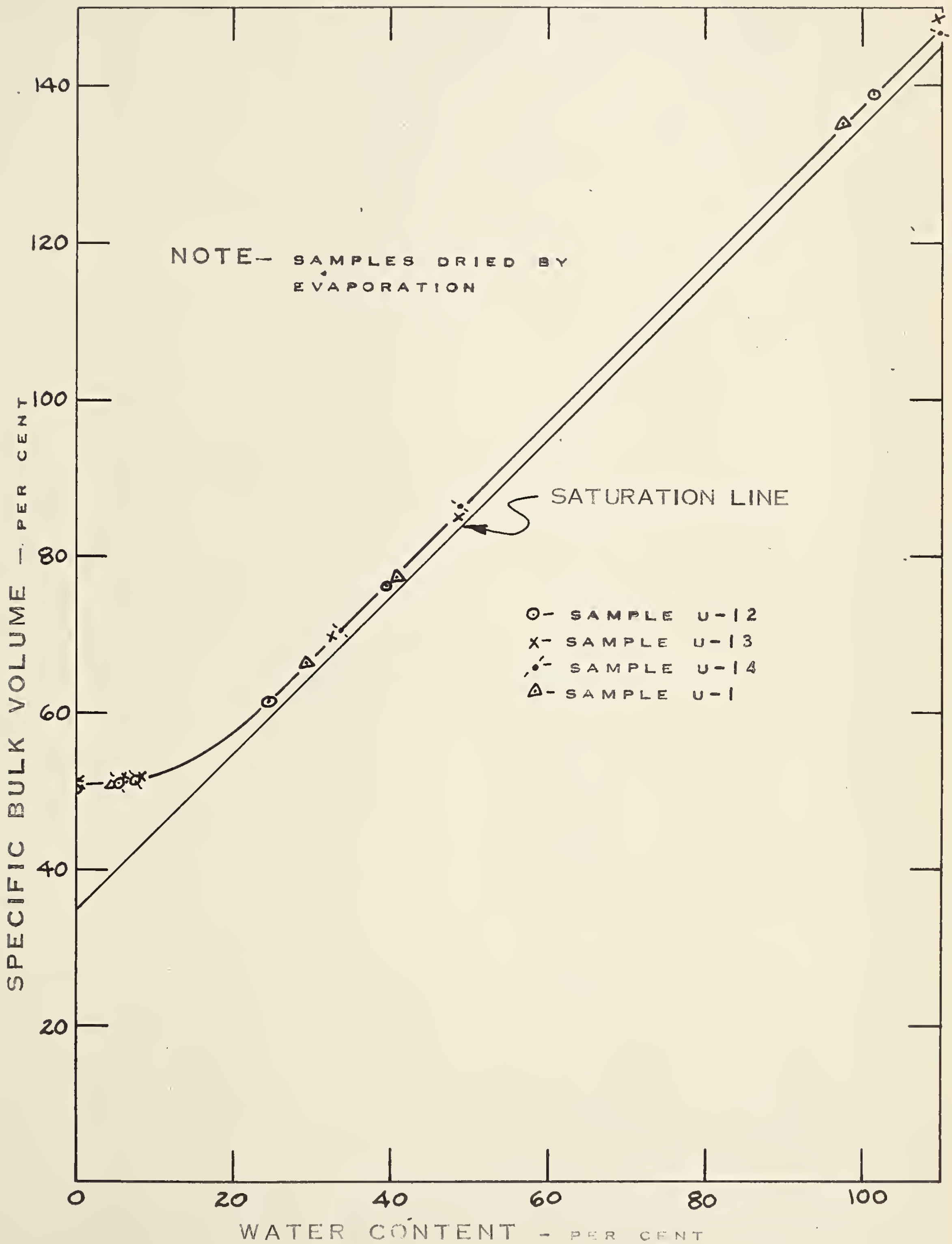


FIGURE 15 SPECIFIC BULK VOLUME VERSUS WATER CONTENT

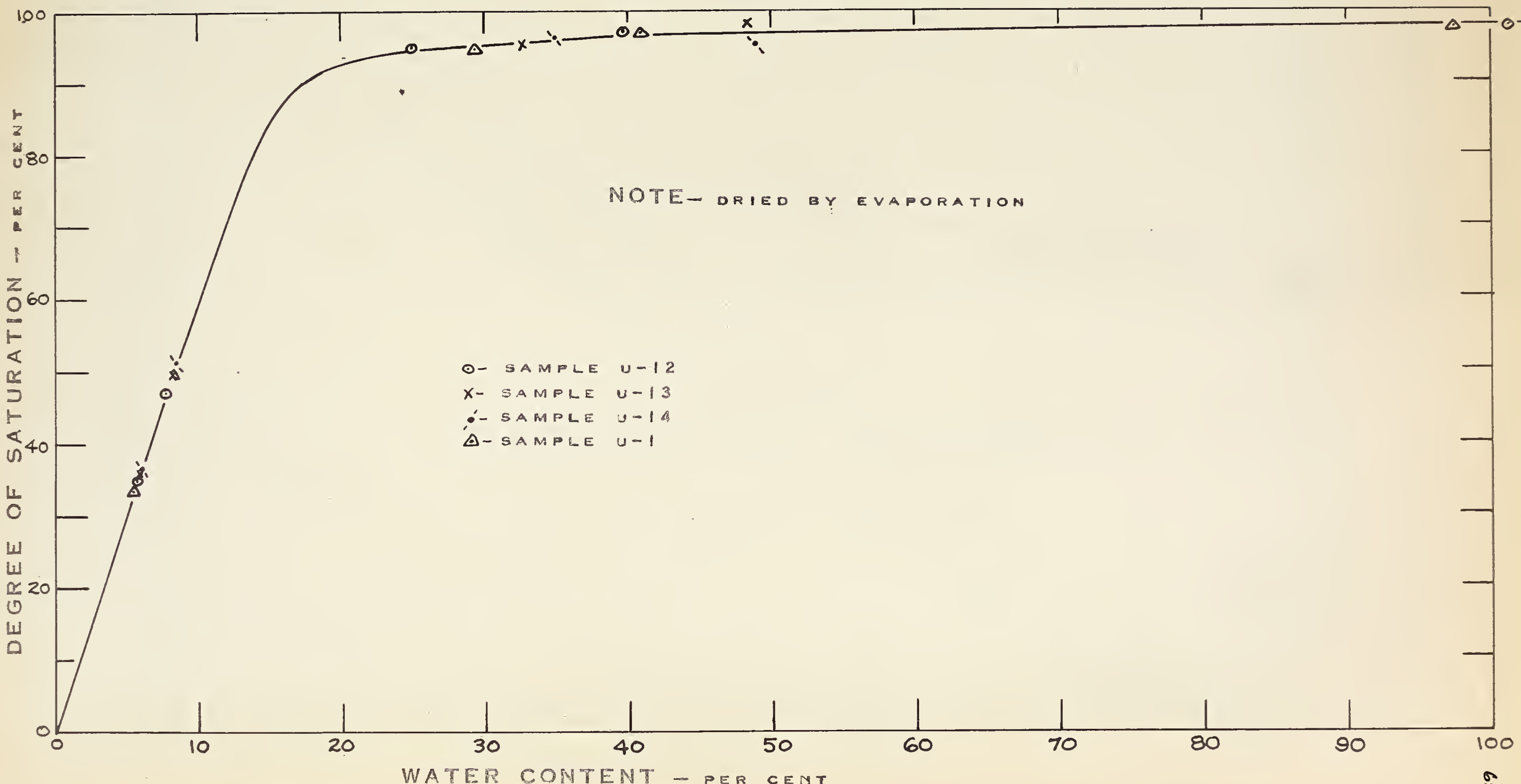


FIGURE 16 DEGREE OF SATURATION VERSUS WATER CONTENT

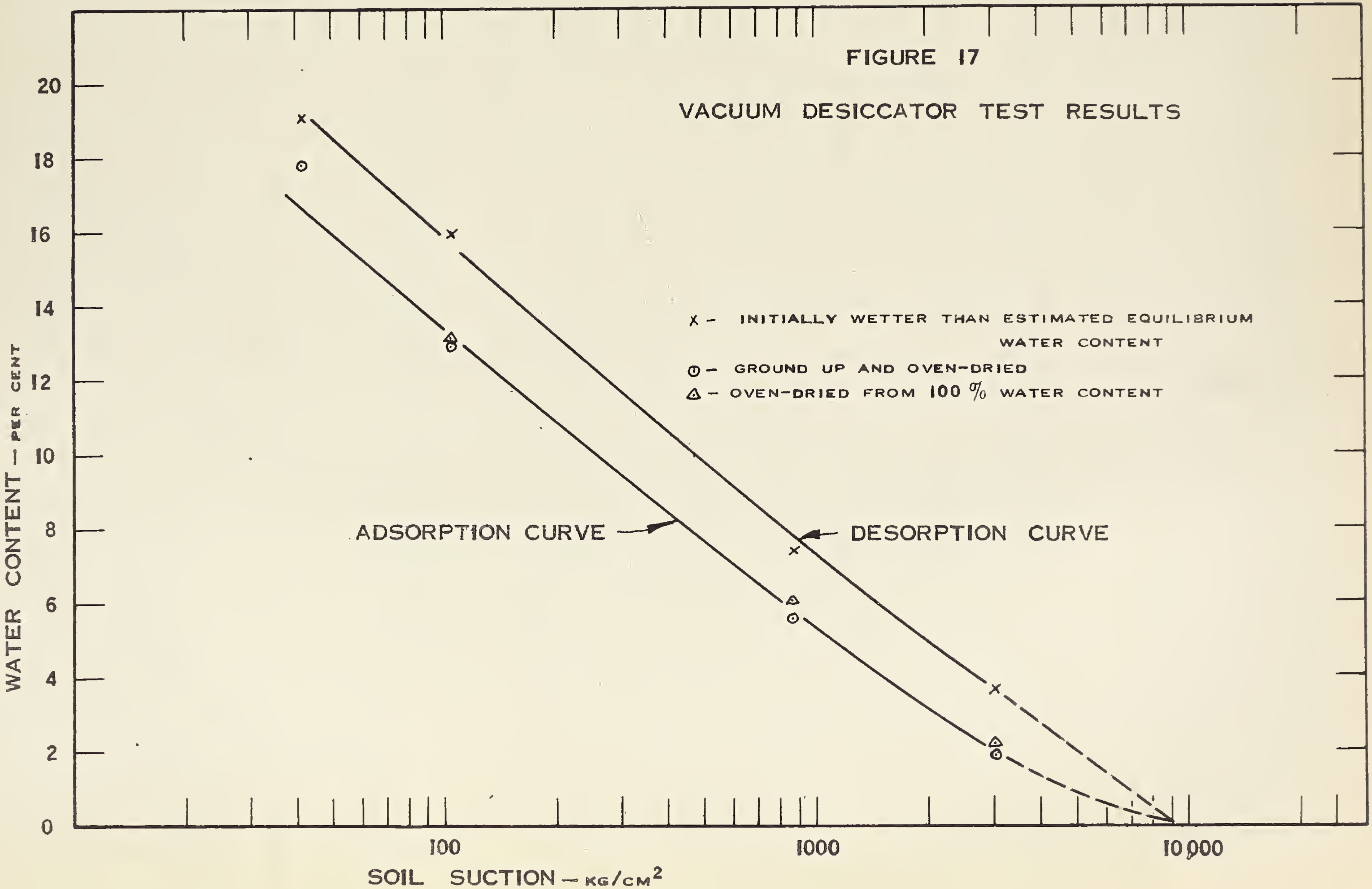


FIGURE 17

VACUUM DESICCATOR TEST RESULTS

than 12 kg/cm^2. Both the desorption and the adsorption curve are shown with a difference between them of about 2 per cent in terms of water content. No volume measurement could be taken but an estimate of the degree of saturation is possible from the previously obtained relationship between degree of saturation and water content.

6:5 One-Dimensional Consolidation Test Results

The one-dimensional consolidation results are shown on FIGURE 18 on a plot of water content versus log effective pressure. No corrections have been applied to compensate for the compressibility of apparatus and filter paper and the effects of side friction at this time. Five tests were performed and the scatter of results on the virgin compression branch is about $\pm$ 1 per cent from the best-fit line. The recompression branches shown are very flat up to the preconsolidation load and then break slope quickly onto the virgin compression branch. All rebound curves are omitted from the plot because there are no similar curves from the suction tests for comparison. A complete summary of numerical values for the consolidation tests is found in Appendix G.

6:6 Rate of Consolidation Results In The Suction Test

The object of this portion of the work is to apply Terzaghi's theory to the rate of consolidation observed in the suction test. In presenting the results, it was found difficult to assess a numerical value to the time consolidation characteristics of the soil. Other investigators such as Leonards and Girault (1961) and Matlock and Dawson (1951) present their results by showing how a typical time consolidation curve fits Terzaghi's theory and then present the remainder of data in terms of con-

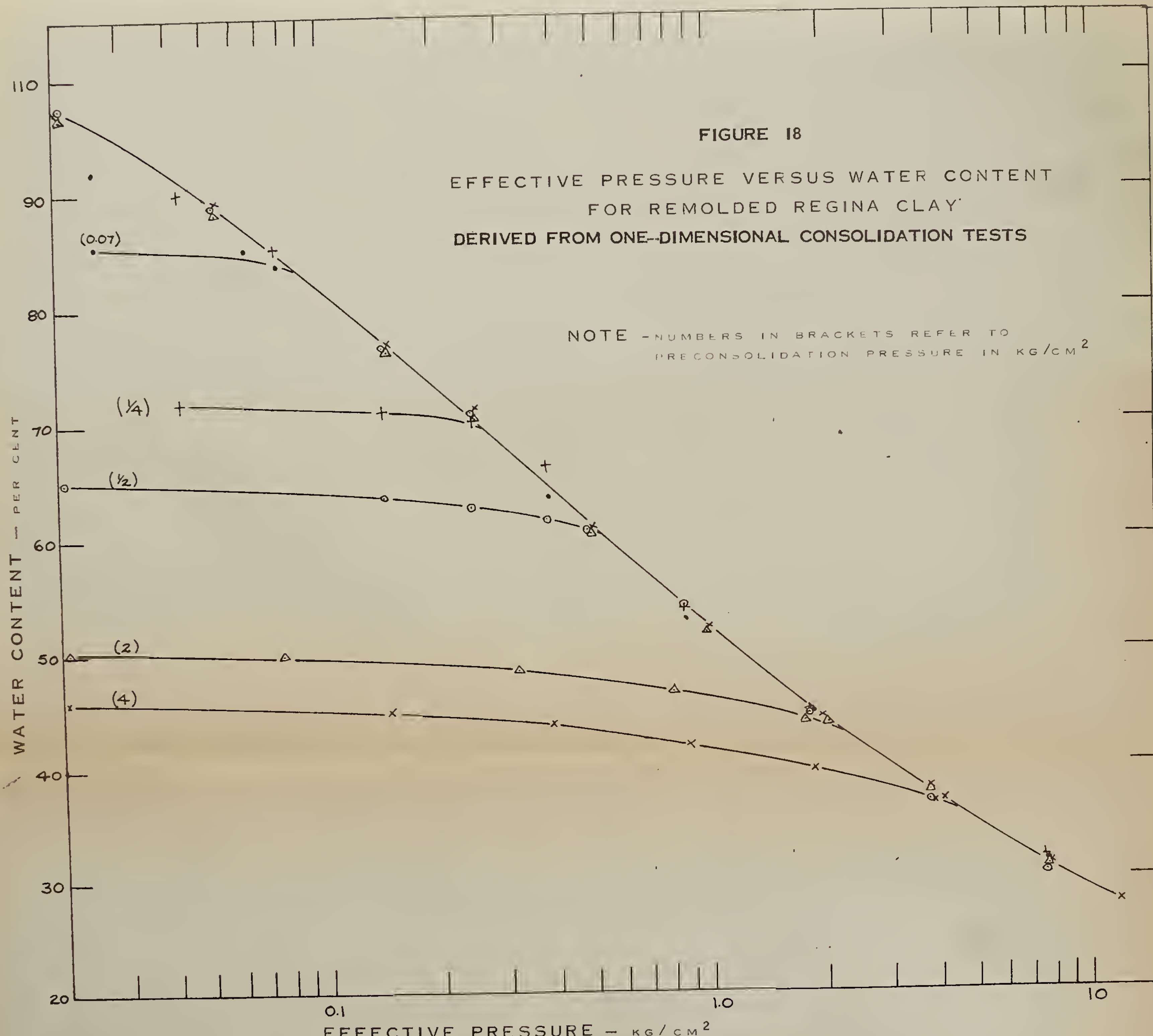


FIGURE 18

EFFECTIVE PRESSURE VERSUS WATER CONTENT FOR REMOLDED REGINA CLAY

DERIVED FROM ONE-DIMENSIONAL CONSOLIDATION TESTS

solidation characteristic such as the coefficient of consolidation.

The rate of consolidation characteristics of the soil were measured on the new pressure plate apparatus. Measurements on the permeability of the porous stone showed it to be over 100 times greater than the soil and thus it was felt that it would not introduce significant error in the results. FIGURE 19 shows a typical plot of log time versus volume change. The theoretical consolidation curve has been fitted to the 50 per cent consolidation point and extrapolated back to zero and forward to 100 per cent consolidation. Discrepancies as much as 3 per cent occur at both high and low percentages of consolidation. However, even if the fitting curve method showed very close correlation it would not necessarily mean the rate of consolidation is the same as in the one-dimensional consolidation test. The factors affecting the rate of consolidation are the length of drainage path and soil properties related to the time to a certain per cent consolidation. The soil property which takes both these factors into account is the coefficient of consolidation which can be determined either by the log or square root of time method. FIGURE 20 shows the coefficient of consolidation versus soil suction for all cases where the load increment ratio was one. Although the coefficient of consolidation results scatter considerably, there appears to be a definite decrease in the coefficient of consolidation with an increase in soil suction. The results obtained by both the log and square root of time method show very similar results and only results from the log of time method will be used in further calculations related to the interpretation of results.

Another graphical method used to present the rate of consoli-

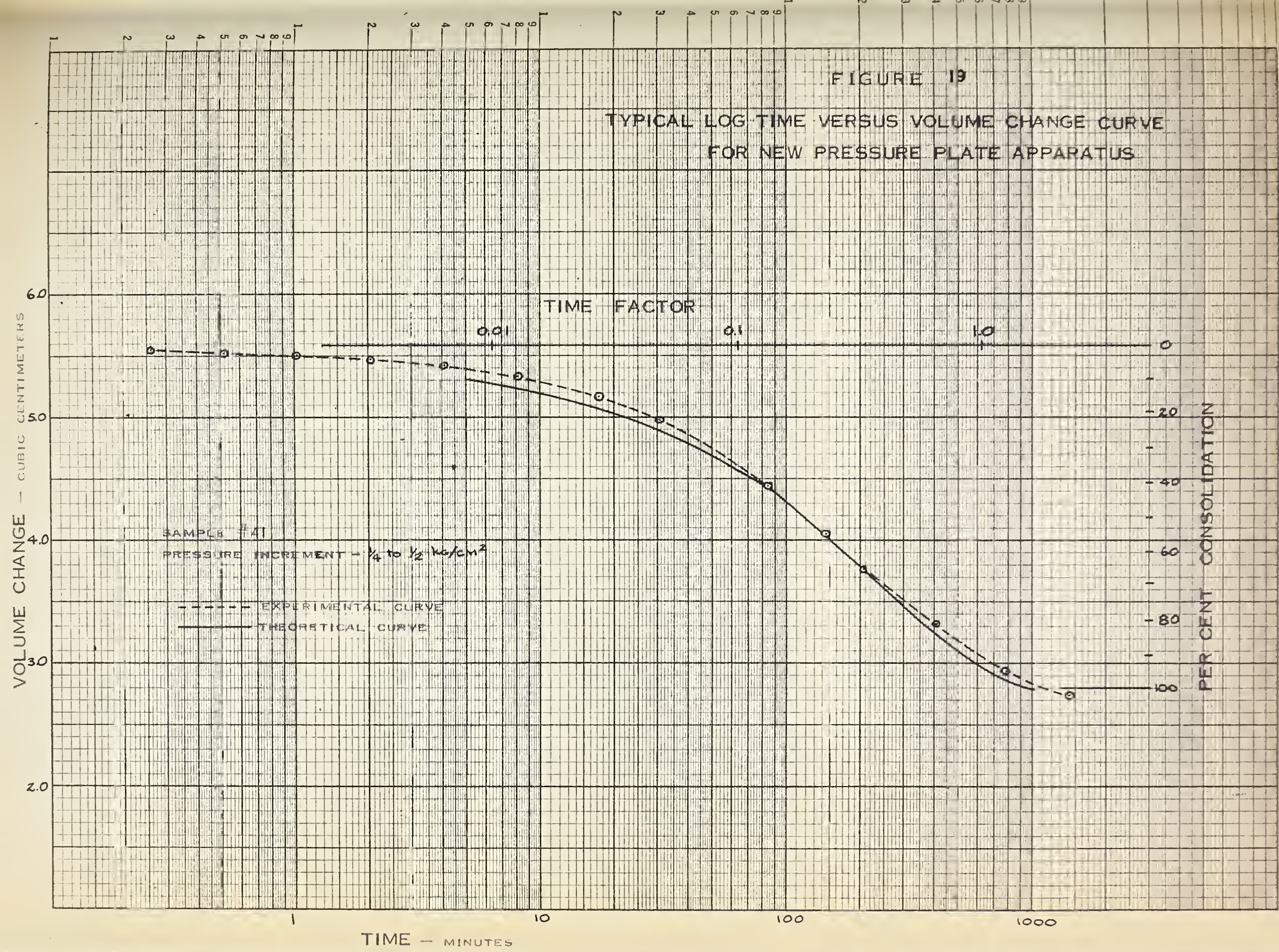


FIGURE 19
TYPICAL LOG TIME VERSUS VOLUME CHANGE CURVE
FOR NEW PRESSURE PLATE APPARATUS
TIME FACTOR
0.01
0.1
1.0
0
20
40
60
80
100
PER CENT CONSOLIDATION
6.0
5.0
4.0
3.0
2.0
VOLUME CHANGE — CUBIC CENTIMETERS
SAMPLE #41
PRESSURE INCREMENT — 1/4 to 1/2 kg/cm²
EXPERIMENTAL CURVE
THEORETICAL CURVE
1
10
100
1000
TIME — MINUTES

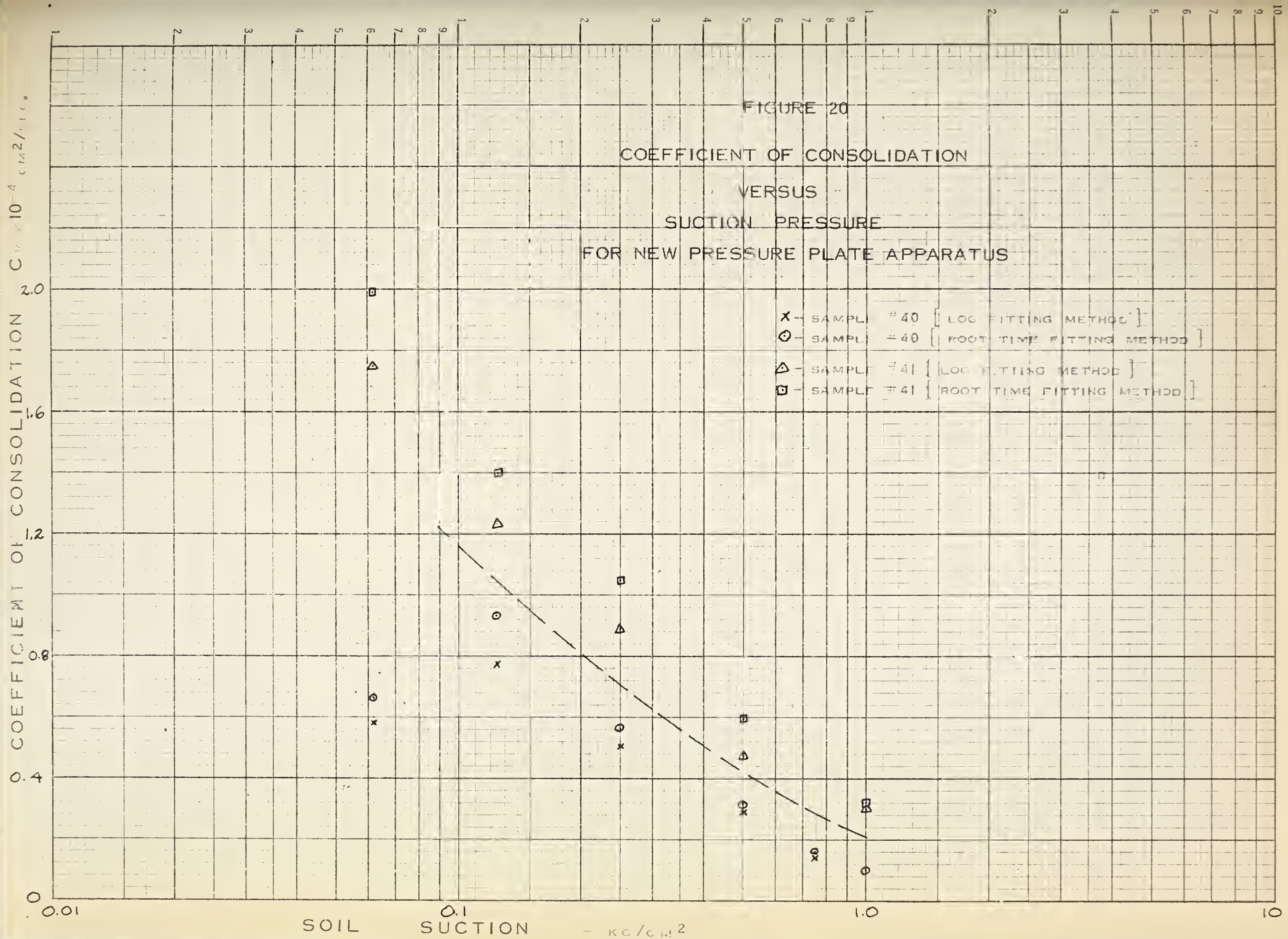


FIGURE 20
COEFFICIENT OF CONSOLIDATION
VERSUS
SUCTION PRESSURE
FOR NEW PRESSURE PLATE APPARATUS
X - SAMPLE #40 [LOG FITTING METHOD]
⊙ - SAMPLE #40 [ROOT TIME FITTING METHOD]
△ - SAMPLE #41 [LOG FITTING METHOD]
⊡ - SAMPLE #41 [ROOT TIME FITTING METHOD]
COEFFICIENT OF CONSOLIDATION
0
0.4
0.8
1.2
1.6
2.0
0.01
0.1
1.0
10
SOIL SUCTION - KG/CM²

dation results was to plot the log time versus amount of consolidation to a common base on one graph. The base chosen was 50 per cent consolidation. Examples of this method of comparison of results are shown in FIGURE 21 and 22.

ONE-DIMENSIONAL CONSOLIDATION RESULTS

The one-dimensional consolidation results are presented in a manner similar to that described for the suction test results. FIGURE 23 shows a typical plot of log time versus consolidation. Terzaghi's theoretical curve lies essentially on top of the test results in the region up to theoretical 100 per cent consolidation.

FIGURE 24 shows a plot of the Coefficient of Consolidation versus the Effective Pressure and the results appear to vary over a much smaller range than those from the suction test. FIGURES 25 and 26 show plots of log time versus consolidation reduced to the common base of 50 per cent consolidation. Further comparisons of the test results from the suction and one-dimensional consolidation tests will be shown and explained in the following chapter.

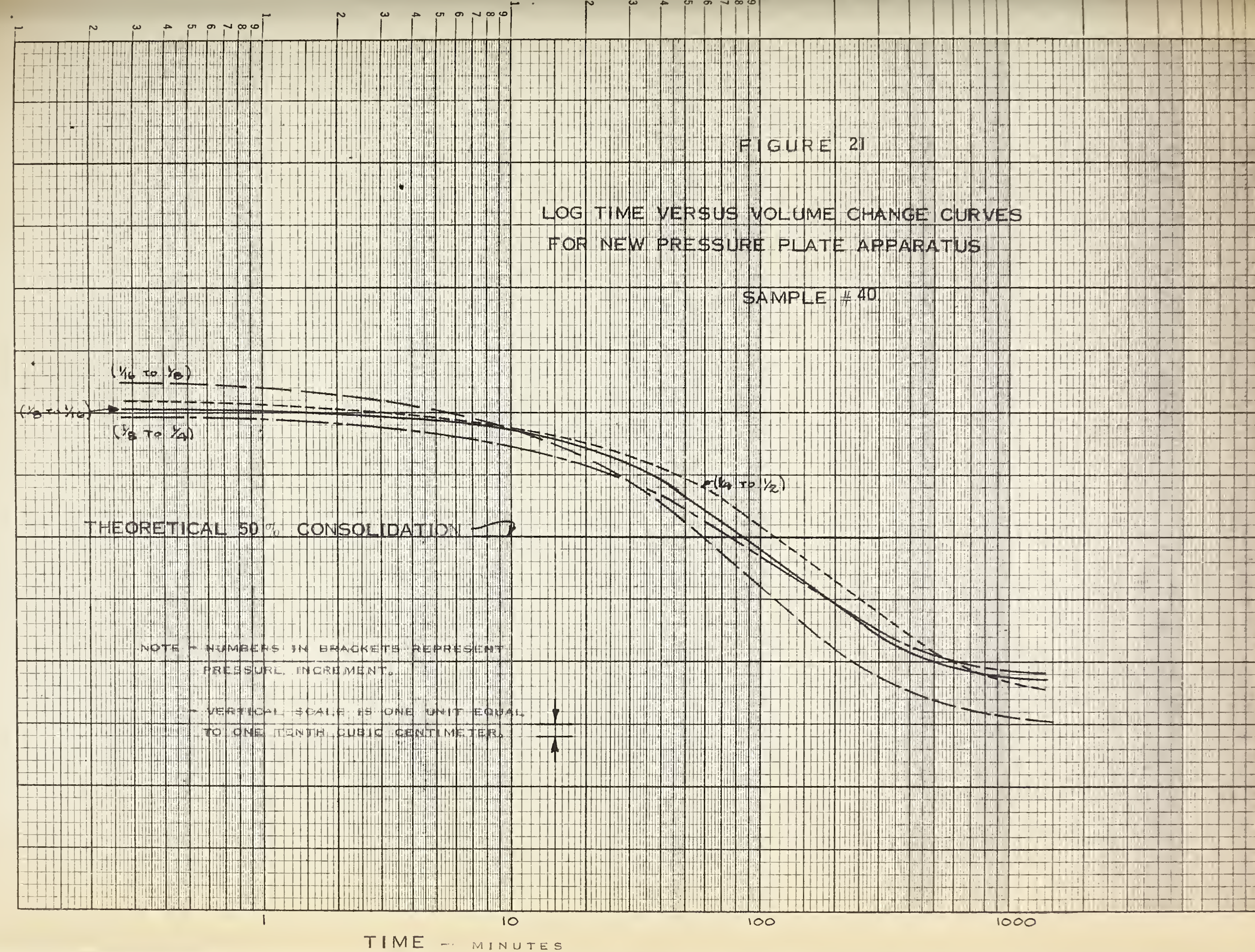
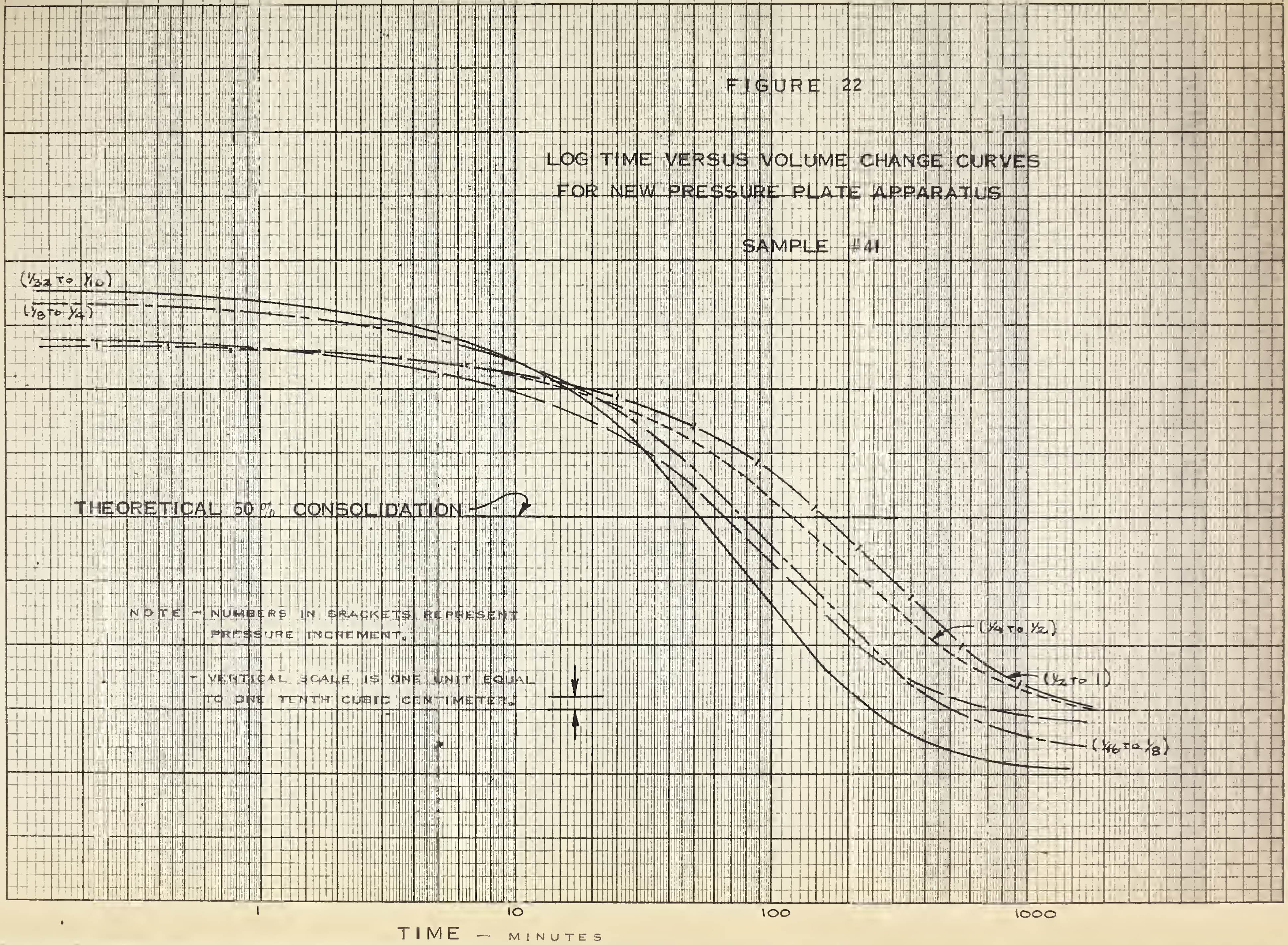


FIGURE 21
LOG TIME VERSUS VOLUME CHANGE CURVES
FOR NEW PRESSURE PLATE APPARATUS
SAMPLE # 40
(1/16 TO 1/8)
(1/8 TO 1/16)
(1/8 TO 1/4)
(1/4 TO 1/2)
THEORETICAL 50 % CONSOLIDATION
NOTE — NUMBERS IN BRACKETS REPRESENT PRESSURE INCREMENT.
— VERTICAL SCALE IS ONE UNIT EQUAL TO ONE TENTH CUBIC CENTIMETER.
1
10
100
1000
TIME — MINUTES

FIGURE 22

LOG TIME VERSUS VOLUME CHANGE CURVES
FOR NEW PRESSURE PLATE APPARATUS

SAMPLE #41



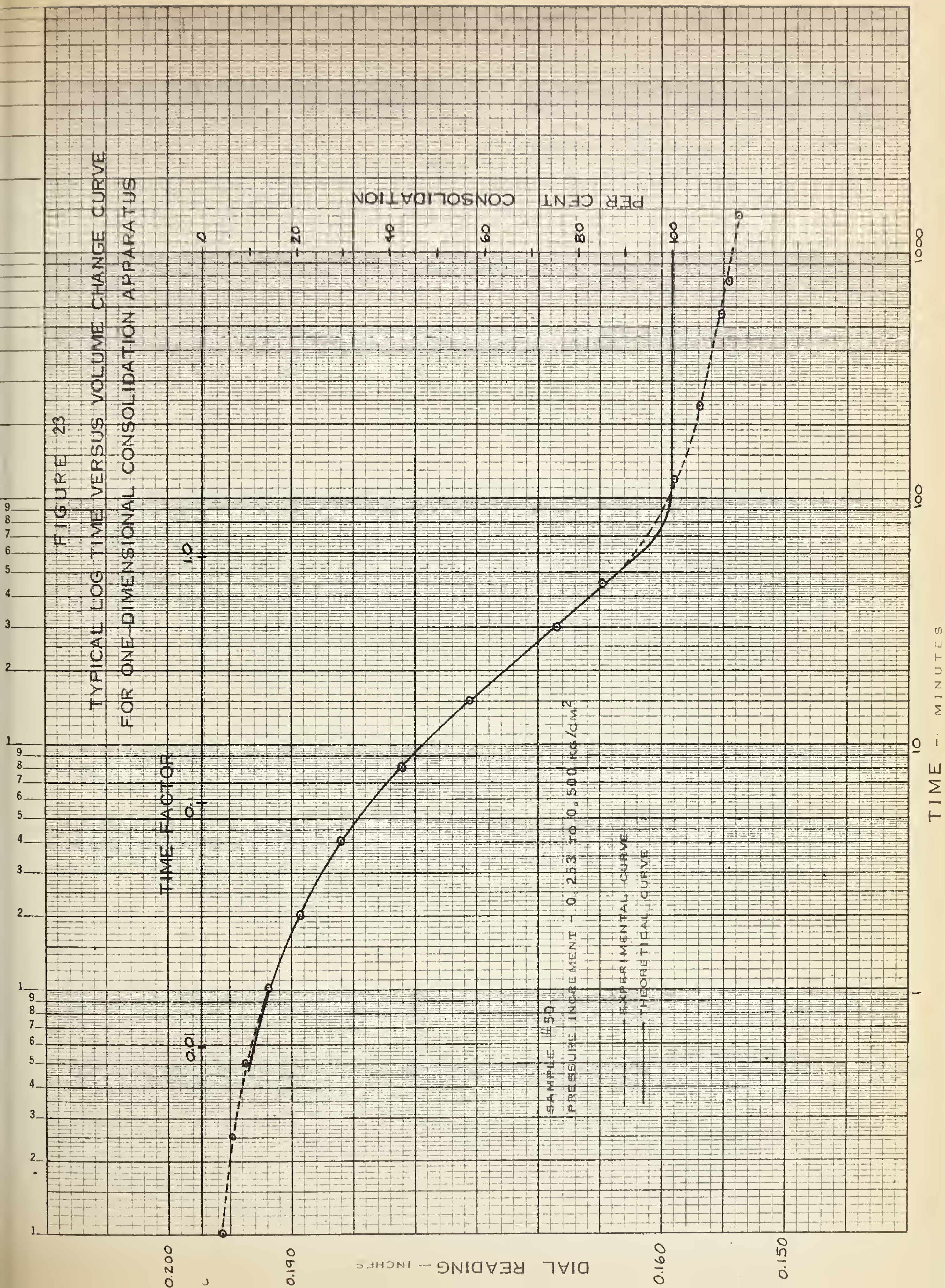


FIGURE 23
TYPICAL LOG TIME VERSUS VOLUME CHANGE CURVE
FOR ONE-DIMENSIONAL CONSOLIDATION APPARATUS

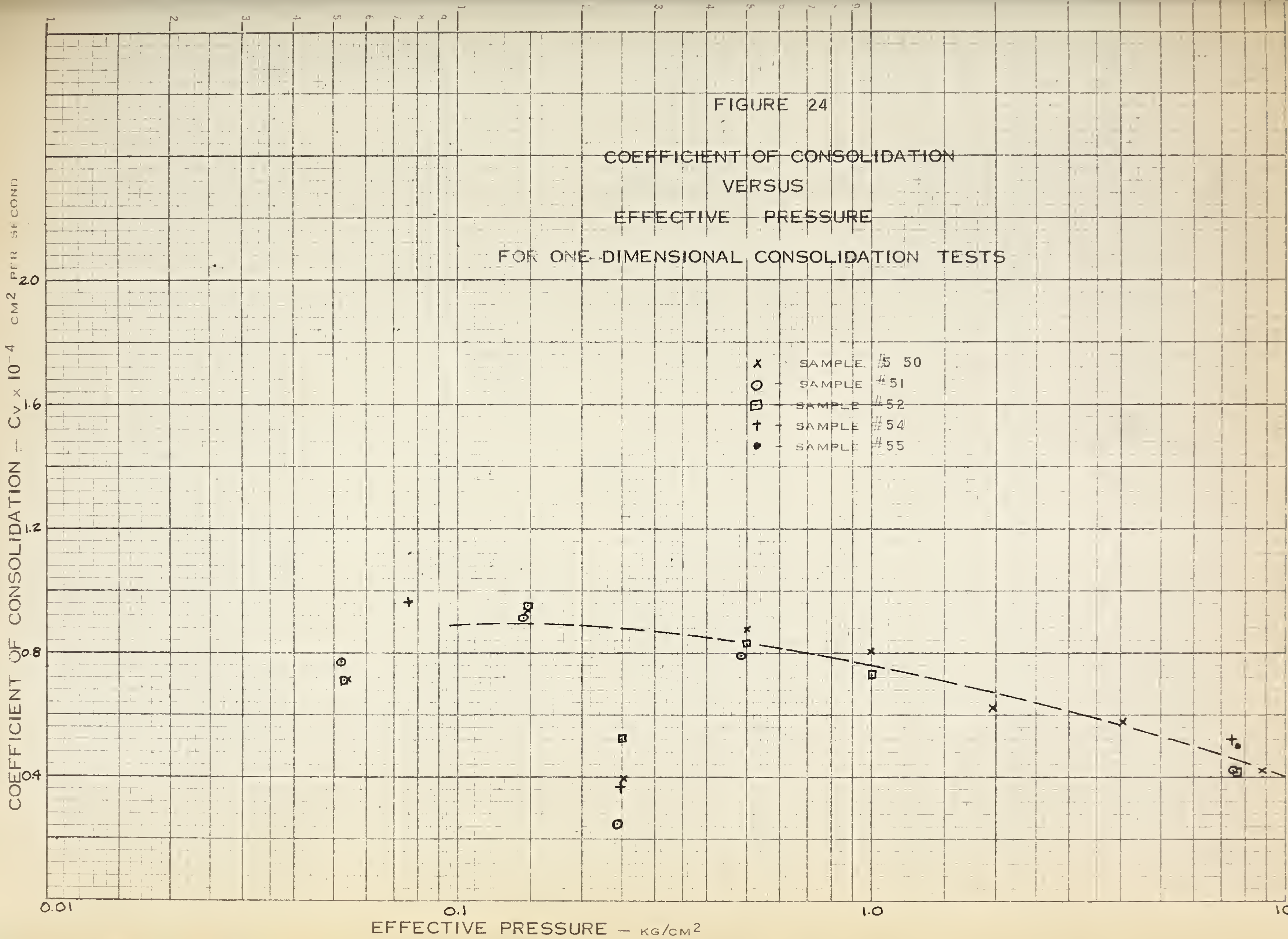


FIGURE 24
COEFFICIENT OF CONSOLIDATION
VERSUS
EFFECTIVE PRESSURE
FOR ONE-DIMENSIONAL CONSOLIDATION TESTS
x - SAMPLE #5 50
⊙ - SAMPLE #51
⊡ - SAMPLE #52
+ - SAMPLE #54
• - SAMPLE #55
COEFFICIENT OF CONSOLIDATION — Cv x 10^-4 CM2 PER SECOND
2.0
1.6
1.2
0.8
0.4
0.01
0.1
1.0
10
EFFECTIVE PRESSURE — KG/CM2

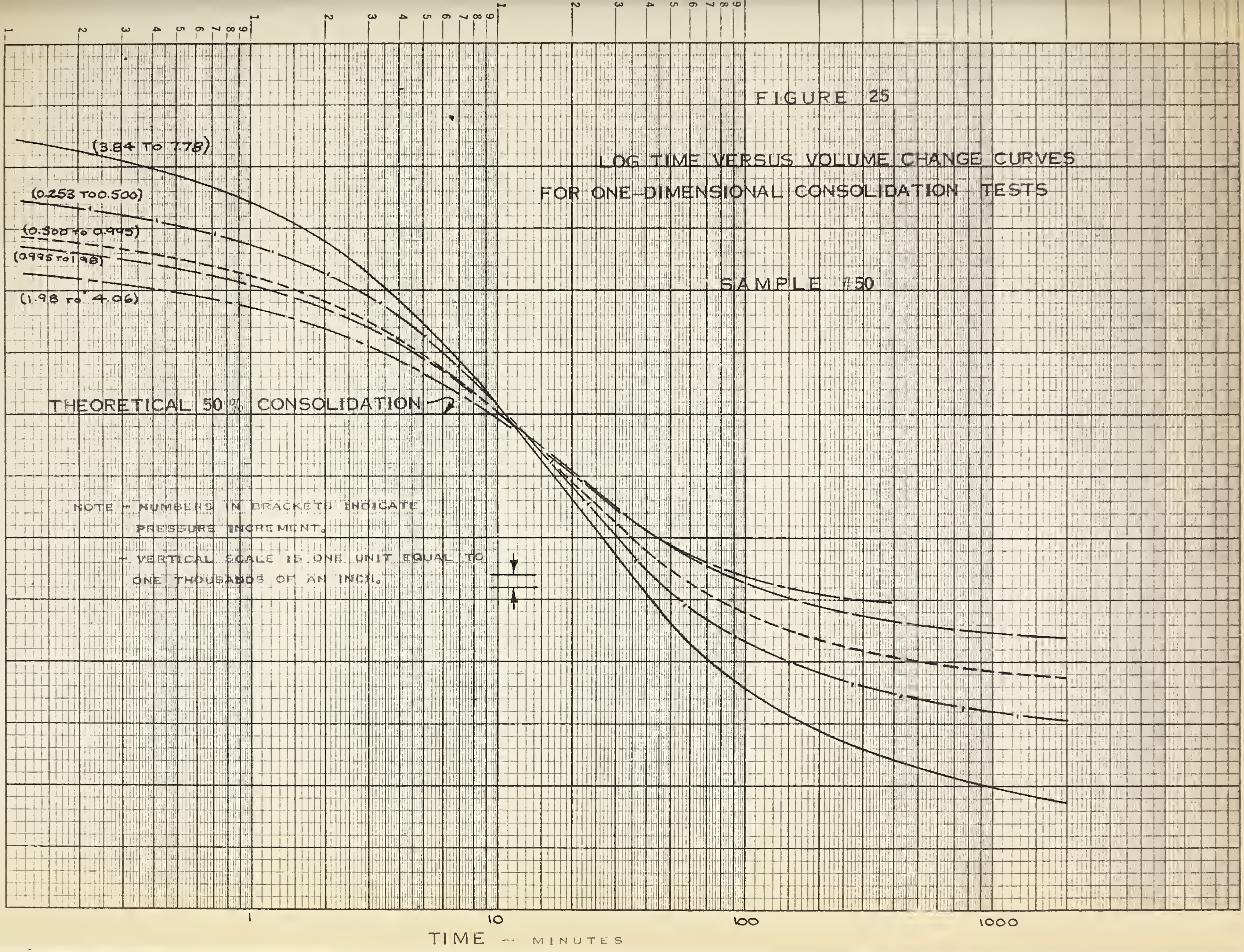


FIGURE 25
LOG TIME VERSUS VOLUME CHANGE CURVES
FOR ONE-DIMENSIONAL CONSOLIDATION TESTS
SAMPLE #50
(3.84 TO 7.78)
(0.253 TO 0.500)
(0.500 TO 0.995)
(0.995 TO 1.98)
(1.98 TO 4.06)
THEORETICAL 50 % CONSOLIDATION
NOTE - NUMBERS IN BRACKETS INDICATE
PRESSURE INCREMENT.
- VERTICAL SCALE IS ONE UNIT EQUAL TO
ONE THOUSANDS OF AN INCH.
1
10
100
1000
TIME ~ MINUTES

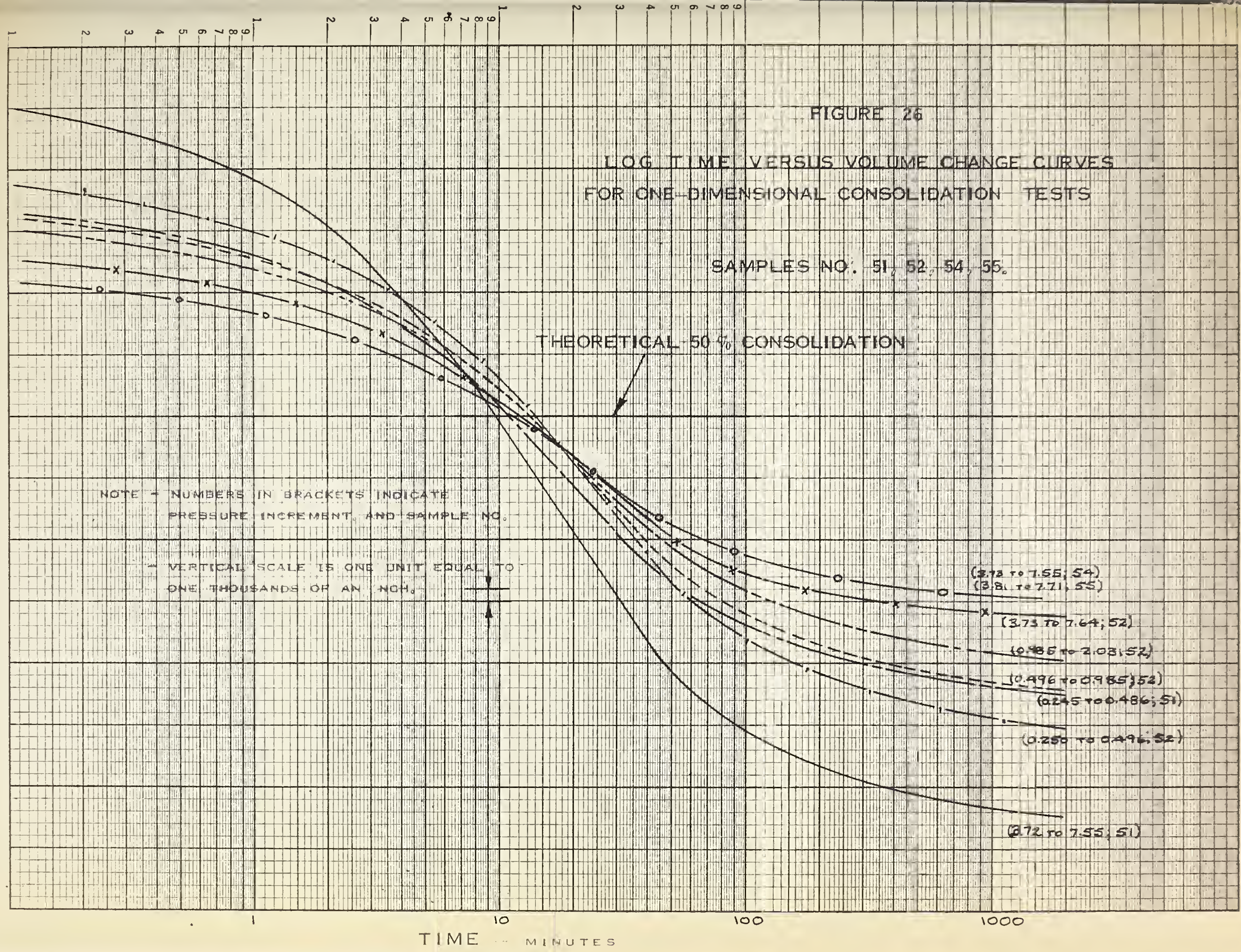


FIGURE 26
LOG TIME VERSUS VOLUME CHANGE CURVES
FOR ONE-DIMENSIONAL CONSOLIDATION TESTS
SAMPLES NO. 51, 52, 54, 55.
THEORETICAL 50 % CONSOLIDATION
NOTE - NUMBERS IN BRACKETS INDICATE
PRESSURE INCREMENT AND SAMPLE NO.
- VERTICAL SCALE IS ONE UNIT EQUAL TO
ONE THOUSANDS OF AN INCH.
(3.73 TO 7.55; 54)
(3.81 TO 7.71; 55)
(3.73 TO 7.64; 52)
(0.985 TO 2.03; 52)
(0.496 TO 0.985; 52)
(0.245 TO 0.486; 51)
(0.250 TO 0.496; 52)
(3.72 TO 7.55; 51)
1
10
100
1000
TIME - MINUTES

CHAPTER VII

INTERPRETATION OF TEST RESULTS

7:1 General

The measured quantities from the testing program were presented in Chapter VI and Chapter VII will discuss the results obtained. The first portion of this chapter deals mainly with the results from the suction tests while the second part discusses their comparison with the one-dimensional consolidation test. Rates of consolidation are compared in the latter portion of this chapter.

7:2 Suction Test Results

The process occurring during a suction test can be explained on the basis of the capillary model previously outlined in Chapter III. During the suction test there are water menisci formed at the surface of the soil due to a difference in pressure between the air above the sample and the water in the soil sample. The radii of these menisci is inversely proportional to the differential pressure at the air-water interphase which induce an effective stress in the soil mass. When dealing with compressible soils, consolidation occurs as the tension in the water phase is increased. Finally a point is reached at which the water menisci receed into the soil. The point of air entry depends upon the proximity of the soil particles and when dealing with a clay material the soil skeleton is able to consolidate and thus prevent the entry of air up to

a high differential pressure.

Samples tested in the laboratory testing program were prepared in the same manner in order to eliminate factors other than those being investigated. For example, it was desirable to have the same soil structure initially in all samples. Therefore, each sample was slurried at a water content of 100 per cent to break down any structure existing in the soil and establish a new uniform structure for all samples. The samples were formed by one-dimensional consolidation to the desired preconsolidation pressures and then rebounded to a very low effective stress. The consolidation process occurring once the samples were placed in the suction apparatus was of a three-dimensional nature. In other words, although the samples were initially formed under anisotropic consolidation, they underwent isotropic consolidation in the suction test. This may have a marked effect upon the structure of the soil but it should be remembered that whenever consolidation is produced by tension being placed on the water phase, an isotropic consolidation process occurs (Aboshi et al, 1961).

Results from both the pressure plate and pressure membrane extractors are shown on FIGURE 7. The reliability of both pieces of equipment is discussed in Appendix E. Both techniques were felt to possess approximately the same accuracy with scatter in the results in the order of $\pm$ 1.5 per cent in terms of water content. The purpose for duplicating many of the test was to obtain a better understanding of the reliability of the technique used since very limited information was available on this equipment. Due to the duplication of tests and improvements to the equipment, the writer feels the best-fit line through the suction test results

are accurate within one per cent in terms of water content.

The total volume of the samples at each equilibrium water content was measured by mercury immersion. The accuracy of the measurements is fully discussed in Appendix E. It was desirable to calculate the specific bulk volume rather than the void ratio in each test since the specific bulk volume is referenced to the same base as the water content determination. Both the water content and specific bulk volume are referenced to the dry weight of soil solids and thus the best results can be plotted to the same scale on one plot and the divergence of the two lines will give a measurement of the change in the degree of saturation. Referring to FIGURES 9 and 10, it is seen that both relationships produce essentially parallel lines, thus making it of no significant value to plot both relationships for all tests. It is important to keep the degree of saturation of a soil in mind when discussing the results because soils at the same water content having different degrees of saturation behave differently (Cooling, 1960). The effective stress relationship for a partially saturated soil must take into acoount the stress in the air phase as well as the water phase once the soil is dried below the "critical degree of saturation" (Aitchison, 1961). For clays the critical degree of saturation has been found to be between 80 and 90 per cent saturation. Drying of the sample in the pressure plate and pressure membrane extractors showd all degrees of saturation to be above 90 per cent. If the critical degree of saturation was assumed to be 85 per cent, it would not be reached until the soil was dried to approximately 18 per cent water content. From the suction versus water content plot this corresponds to a soil

suction value of 60 kg/cm^2. From the above reasoning it would appear that a soil should consolidate in accordance with Terzaghi's equation for effective stresses.

The suction curve for a highly plastic clay (LL = 75%) was performed by Croney et al (1958). His results check within ± 5% of those obtained for Regina clay. Similar to the data from the testing program in this thesis, his results show a continuous curving of the recompression branch as it is reconsolidated to the virgin compression branch. This is quite different than the type of curve obtained from the one-dimensional consolidation test, but no explanation is given in Croney et al's report for this behavior. This point will be more fully discussed later in this thesis in connection with the comparison of the suction test results with the one-dimensional consolidation test results.

Black et al (1958) stated that for a given soil, the factors affecting the suction versus water content relationship were the particle size and the initial density. In the testing program only one soil type was used which was thoroughly mixed to essentially eliminate variations in the particle distribution. Therefore, the main variable in the test results is the variation in initial density or in other words water content. Consolidation from various initial water contents converge on the virgin compression branch. The relationship between preconsolidation pressures and initial rebounded water content for the suction tests is shown on FIGURE 27 and complete numerical results are tabulated in Appendix H. The initial water content was measured by two methods and both results are shown. One method involved the determination of initial

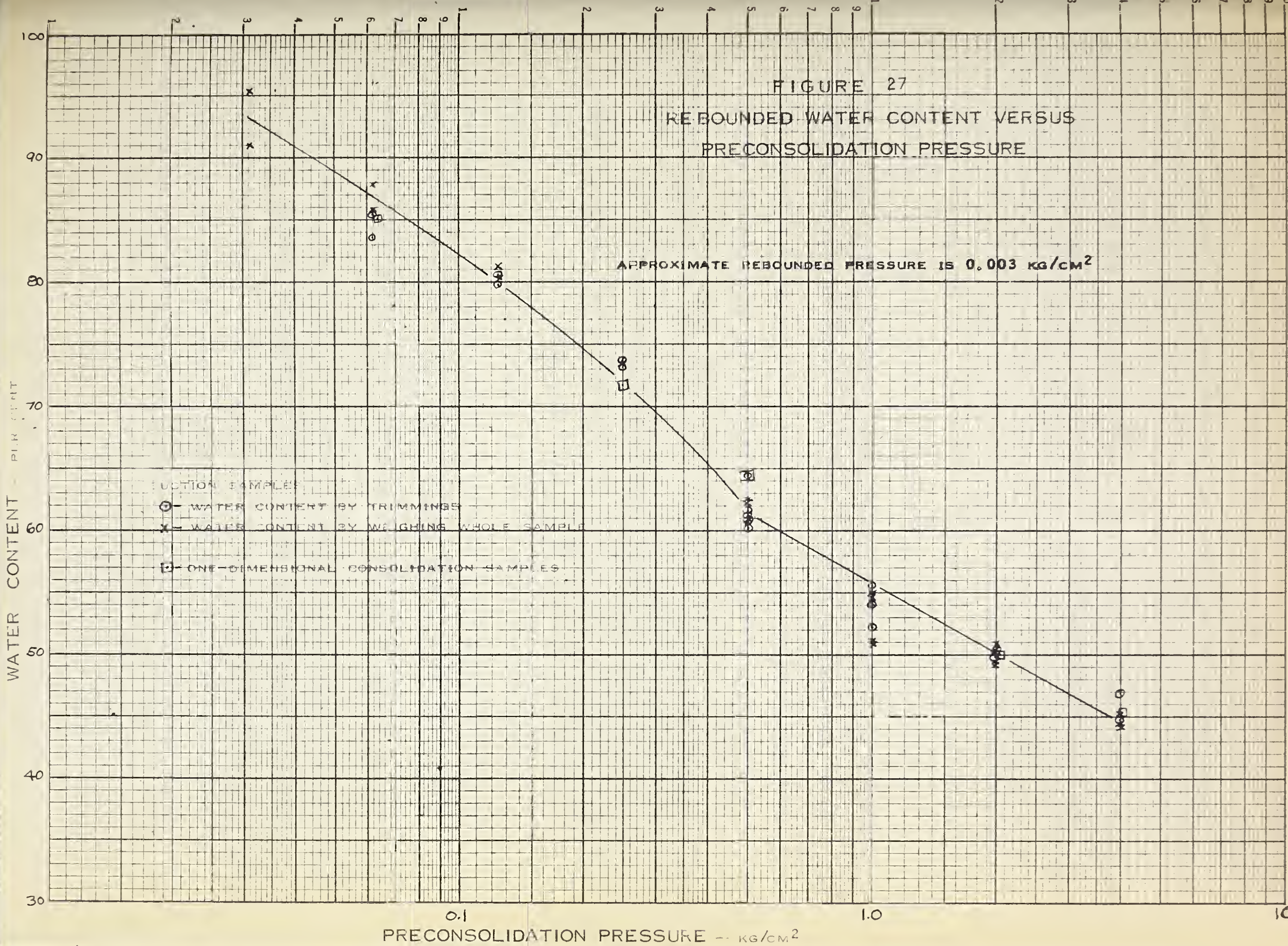


FIGURE 27
REBOUNDED WATER CONTENT VERSUS
PRECONSOLIDATION PRESSURE
APPROXIMATE REBOUNDED PRESSURE IS 0.003 KG/CM^2
WATER CONTENT BY TRIMMINGS
WATER CONTENT BY WEIGHING WHOLE SAMPLE
ONE-DIMENSIONAL CONSOLIDATION SAMPLES
WATER CONTENT
PRECONSOLIDATION PRESSURE -- KG/CM^2
100
90
80
70
60
50
40
30
0.1
1.0
10

water content from trimmings during the preparation of the sample while the other involved the weighing of the whole sample used for the suction test. The second method is felt to be more reliable because a larger samples was weighed which would undergo less drying during preparation for the suction test. The scatter of the initial water contents is felt to be due to an inaccurate knowledge of the actual preconsolidation pressure on the sample. The friction on the side walls of the lucite consolidation rings in which the samples were prepared was found to cause variations in the water content of the samples varying by $\pm$ 1 per cent throughout the sample. Also, the consolidation equipment was of the old PFRA design and had considerable friction in the moving parts. Effects related to the equipment are felt to be more significant than the variations in the properties of the soil.

The initial water content versus log preconsolidation pressure shows a straight line relationship for preconsolidation pressures in excess of 0.5 kg/cm^2. This means that approximatley the same amount of rebound occurred in each sample regardless of the preconsolidation pressure. Below preconsolidation pressures of 0.5 kg/cm^2 the best-fit line becomes steeper. This would indicate that more rebound actually occurred on the samples with a low preconsolidation pressure.

7:3 Comparison of Drying by Evaporation and Drying in the Suction Apparatus

Drying by evaporation from the soil surface is the main process of desiccation which occurs in the field and is similar to the drying which occurs in the suction test. Several tests show that the relationship between the specific bulk volume and water content is the same for both

methods of drying. Small variations can be noticed easier on the degree of saturation versus water content plot (FIGURE 16) and it is estimated that the degree of saturation in the suction tests is 2 per cent lower than drying by evaporation. If any reason at all can be ascribed to this variation, it is probably related to the fact that at each equilibrium pressure the samples are reduced to atmospheric pressure in order that their wet weight and volume may be measured. However, the difference in results is small and it can be stated that the volume versus water content relationship for drying by evaporation and in the suction test are the same for Regina clay.

7:4 Vacuum Desiccator Results

The addition of the vacuum desiccator test results completes the suction curve down to zero water content as defined by drying at 103°C. The results show that water is held to the soil by extremely high forces at low water contents. FIGURE 17 shows the results obtained by three different methods of sample preparation. The first set of samples which were initially wetted to a water content higher than the estimated equilibrium water content and dried to equilibrium conditions and constitute the desorption suction curve. The other two sets of samples were initially oven-dried and the results constitute the adsorption curve. The difference between the desorption and adsorption curve is about two per cent in terms of water content. Soil science workers have done considerable work on the hysteresis effects occurring when drying and wetting a soil but admit that the phenomena is complicated and further research is necessary before it is fully understood (Staple, 1961). In simple

terms it can be stated that a soil holds more water at a given suction during desorption than during adsorption.

The overall suction curve of FIGURE 8 shows a slight curvature throughout its whole length with a fairly definite break in curvature at a suction of approximately 20 kg/cm^2 which corresponds to a water content of 25 per cent. On the water content versus degree of saturation plot, the saturation begins to decrease at approximately 25 per cent water content with a large decrease occurring at 15 per cent. It is interesting to note that the classification test results show the plastic limit to be 25 per cent and the shrinkage limit to be 13 per cent. Whether there is any correlation between these factors is difficult to say since tests were performed on only one soil. Other research workers have tried to correlate plastic limit with a certain suction value but the results did not appear very promising. Croney et al (1958) suggested a suction value of 2.5 kg/cm^2 at the plastic limit for a highly plastic clay which was "continuously disturbed". For the soil they used this corresponded to a suction of 9.5 kg/cm^2 on the initially slurried compression branch. Other investigators have suggested using quite different values to correspond to the plastic limit but have not had much success (Russam, 1962). A review of data available from other research workers and a discussion of their results is contained in Appendix H. On the basis of the discussion in the appendix, the author feels that the plastic limit of a highly plastic soil has a suction of approximately 16 kg/cm^2.

The suction at the liquid limit was 0.1 kg/cm^2 for Regina clay. Whether there is any relationship between suction and liquid limit is not

known at this time due to the limited number of available results. Discussion of this relationship is also found in Appendix H.

7:5 One-Dimensional Consolidation Results

The one-dimensional consolidation tests were performed in order to compare one-dimensional consolidation with consolidation in the suction test. Previously in this thesis, it was shown that the two methods of consolidation have been treated as different types of consolidation with only sparse information about the relationship between them. In order to perform a comparison, it is necessary to bring both test procedures to the same basis, or in other words, to eliminate or compensate for all secondary variables. The secondary factors in the one-dimensional consolidation test which are not present in the suction test are (i) friction in the mechanical parts, (ii) side friction of the soil in the ring and (iii) compressibility of apparatus and filter paper. Friction in the mechancial parts of the consolidometer was compensated for by measuring the actual pressure delivered to the sample. Details are found in Appendix B.6. Side friction of the soil in the ring is difficult to evalute but information from other research workers was used to approximate its significance (Leonards, 1961; Lambe, 1951). Compressibility of apparatus and filter paper was measured in the laboratory and details of its significance is found in Appendix B.7.

All consolidation results are calculated with correction for the friction in mechanical parts. Since extensive calculations are necessary to correct for side friction and compressibility, only the virgin compression branch of the consolidation curve was corrected for all factors

and is shown in its corrected form on FIGURE 28. For pressure less than 3 kg/cm^2 the virgin compression branch is shifted down and to the left while at pressure in excess of 3 kg/cm^2 it is shifted up and to the left. The corrected curve will be used in the comparison of the virgin compression branches of the suction and one-dimensional consolidation results.

7:6 Comparison of Suction and One-Dimensional Consolidation Test Results

Best fit lines through the suction test data have been prepared on a plastic transparency which can be placed over the one-dimensional consolidation results to aid in comparing the results. These are shown as FIGURES 29 and 30. First it should be noted that the one-dimensional consolidation test imparts anisotropic consolidation to the sample while the suction test imparts isotropic consolidation. Comparison of the two processes of consolidation by Aboshi and Monden in 1961 and also by Bishop and Henkel in 1962 shows that during isotropic consolidation more water is forced out of the soil than by anisotropic consolidation. The amount of the difference between the processes of consolidation depends upon the coefficient of earth pressure at rest of the soil. For remolded clays the coefficient of earth pressure in a one-dimensional consolidation test is listed as approximately 0.70. At high water content anisotropic consolidation should not differ very much from isotropic consolidation. The difference in the amount of consolidation occurring can be best explained in terms of the resultant structure of the soil particles during consolidation. One-dimensional consolidation tends to produce a dispersed structure and it is believed that shear stresses are developed at the particle surfaces as they are reorientated. Specimens isotropically consolidated retain a more flocculated structure with smaller shear stresses

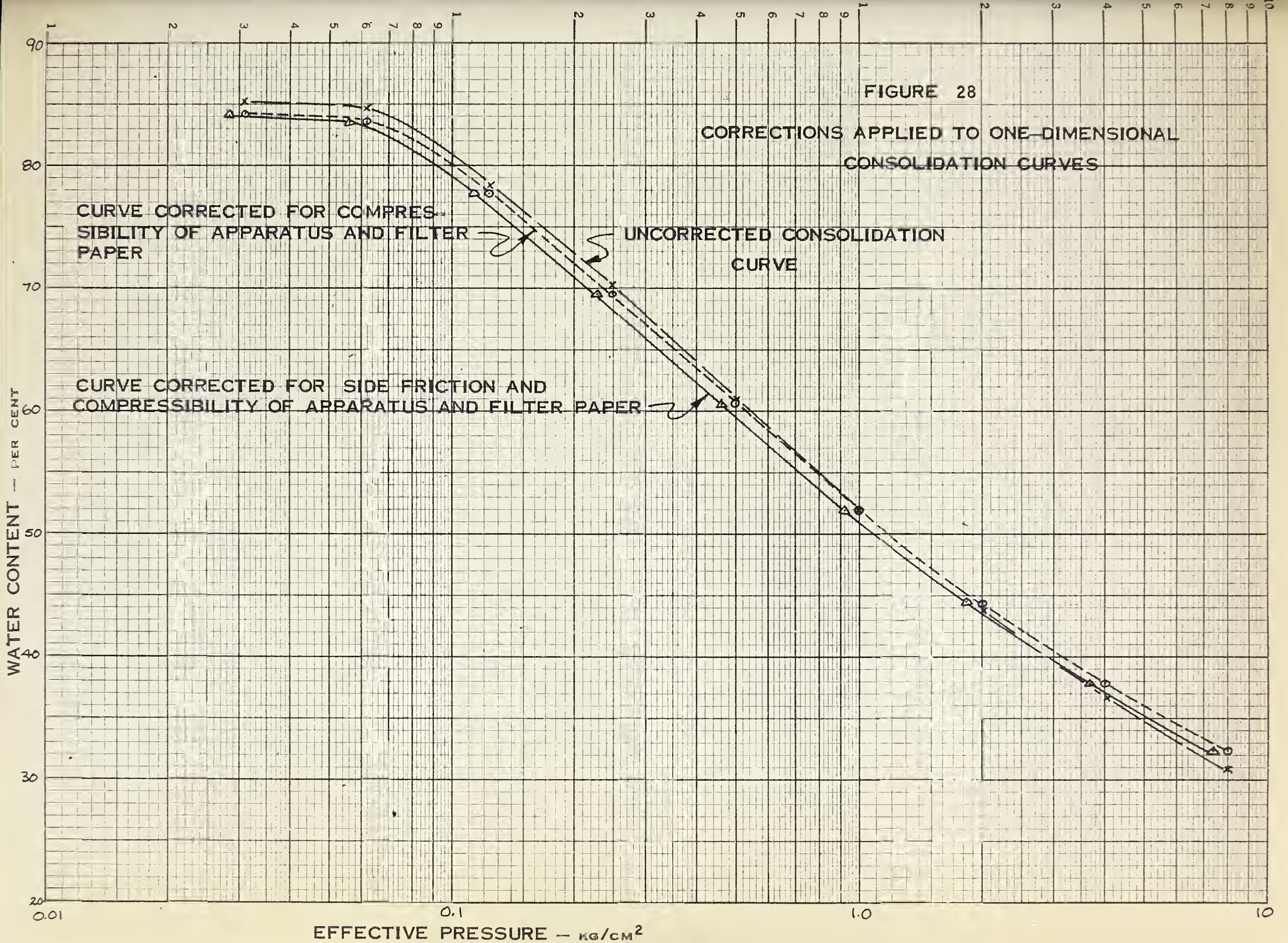


FIGURE 28
CORRECTIONS APPLIED TO ONE-DIMENSIONAL CONSOLIDATION CURVES
CURVE CORRECTED FOR COMPRESSIBILITY OF APPARATUS AND FILTER PAPER
UNCORRECTED CONSOLIDATION CURVE
CURVE CORRECTED FOR SIDE FRICTION AND COMPRESSIBILITY OF APPARATUS AND FILTER PAPER
WATER CONTENT — PER CENT
EFFECTIVE PRESSURE — KG/CM2
90
80
70
60
50
40
30
20
0.01
0.1
1.0
10

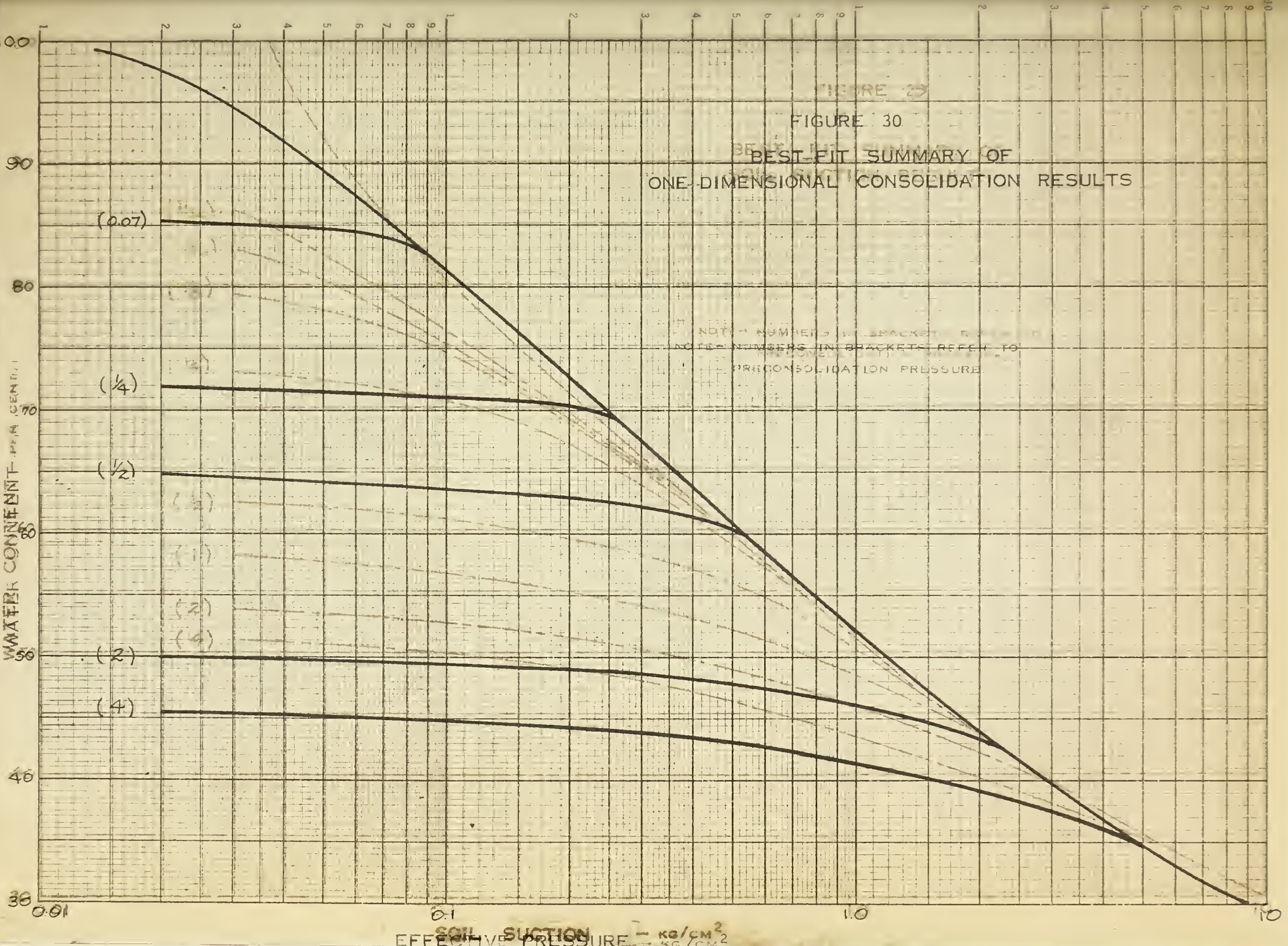


FIGURE 30
BEST-FIT SUMMARY OF
ONE-DIMENSIONAL CONSOLIDATION RESULTS

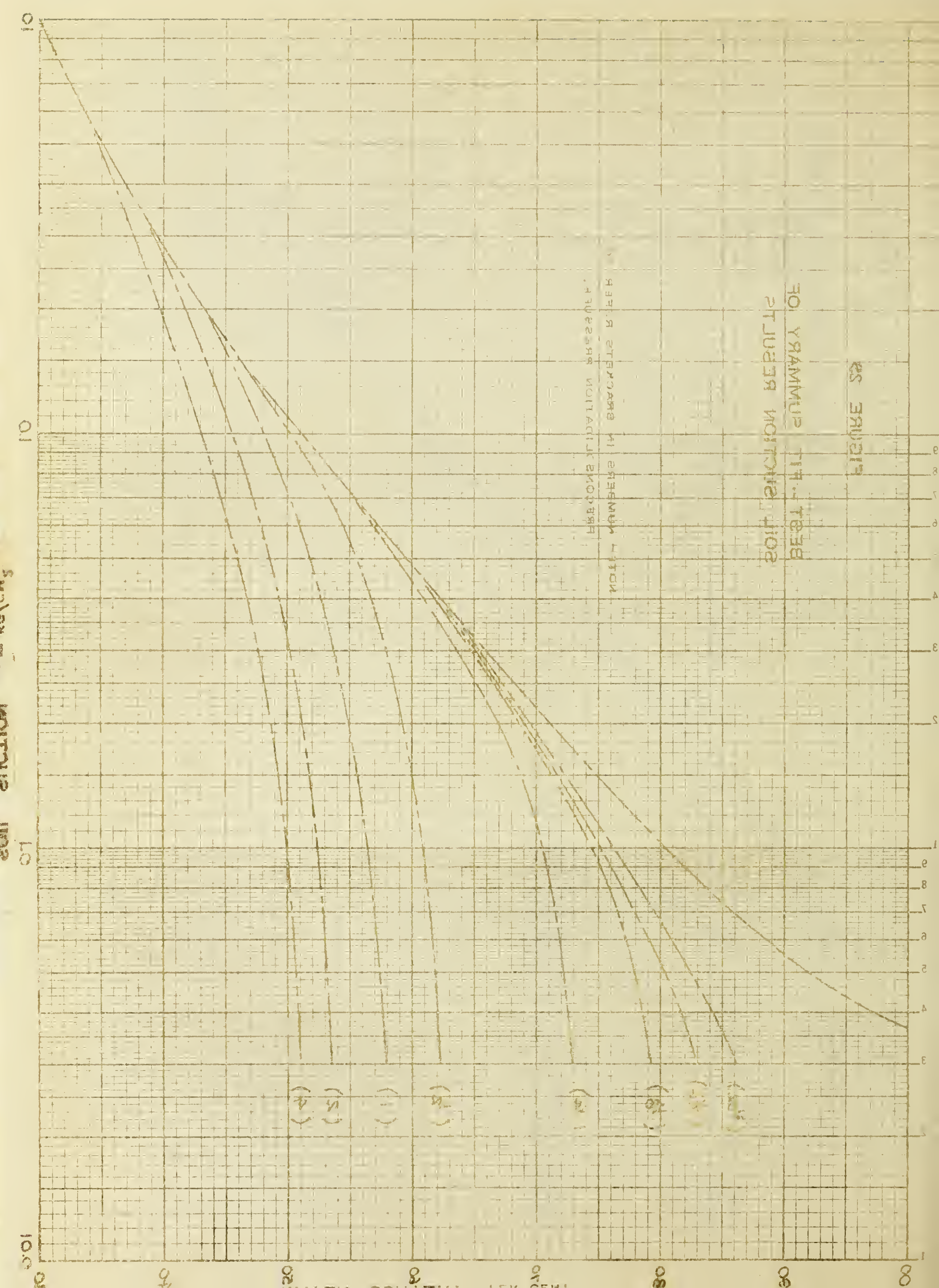


FIGURE 25
BEST-FIT SUMMARY OF
SOIL SUCTION RESULTS
SOIL SUCTION — kg/cm²

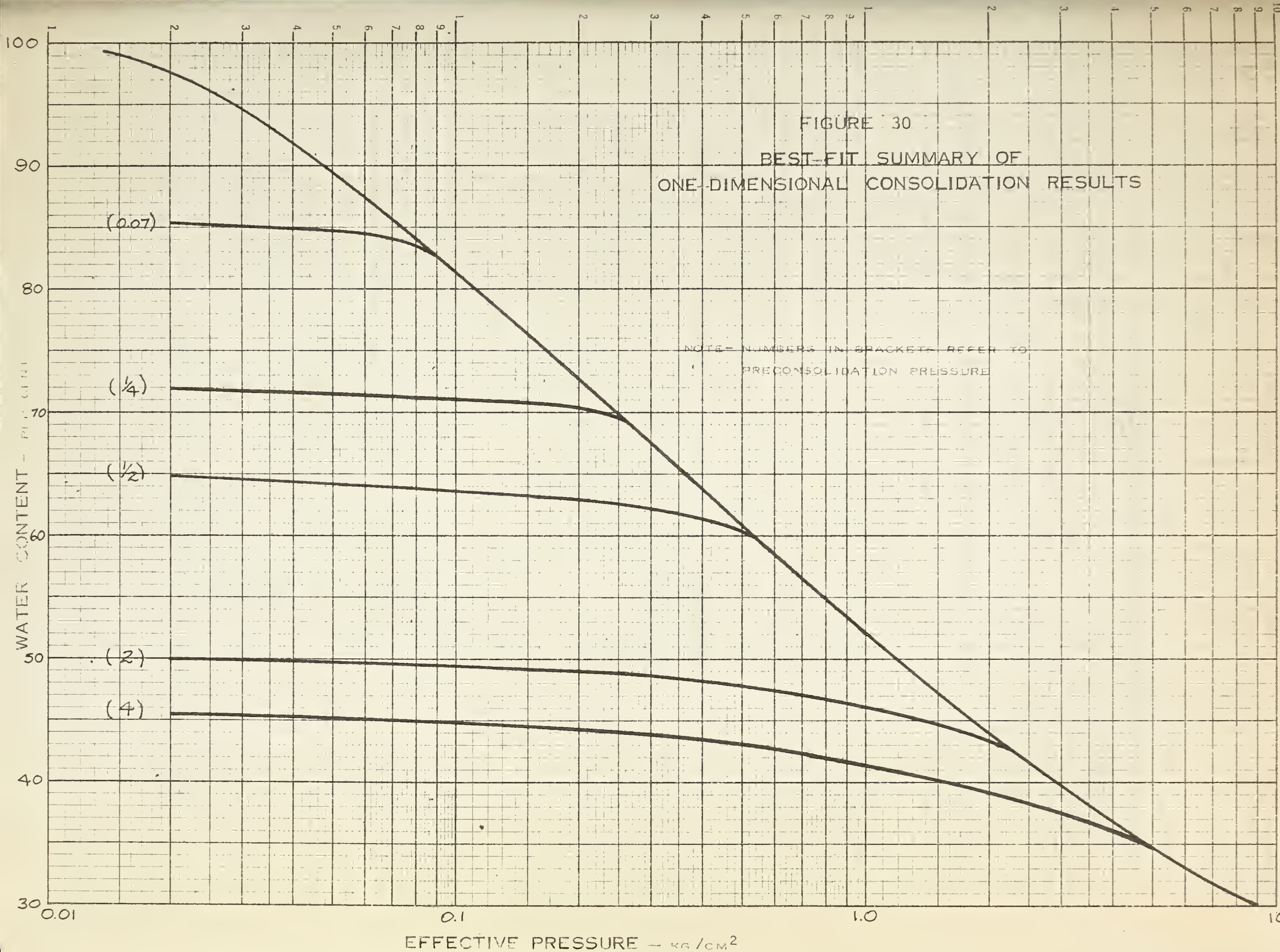


FIGURE 30
BEST-FIT SUMMARY OF
ONE-DIMENSIONAL CONSOLIDATION RESULTS
NOTE – NUMBERS IN BRACKETS REFER TO
PRECONSOLIDATION PRESSURE
(0.07)
(1/4)
(1/2)
(2)
(4)
WATER CONTENT - PER CENT
100
90
80
70
60
50
40
30
0.01
0.1
1.0
10
EFFECTIVE PRESSURE — KG/CM²

at the particle surface.

FIGURE 30 compares a suction and one-dimensional consolidation curve for the soil preconsolidated to 0.626 kg/cm^2. The corrected one-dimensional curve falls directly on top of the suction curve at pressures in excess of 0.5 kg/cm^2 up to a pressure of 10 kg/cm^2. Beyond this point the behavior of the curves is not definitely known since there are no one-dimensional consolidation results.

There appears to be a diversion on the recompression branches of the results shown in FIGURE 31. The suction test shows a much flatter curve and has no distinct break in curvature at the point where the preconsolidation pressure is exceeded. Also, at a certain effective pressure on the recompression branch the suction results have a lower water content than the one-dimensional consolidation test. FIGURE 32 shows the difference in recompression branch for various preconsolidation pressures. Slight adjustments were made in the suction test results in order to make the initial water contents correspond to those of the one-dimensional consolidation test. All recompression branches for the suction tests give lower equilibrium water content conditions on the recompression branch and then join the virgin compression branch at a pressure considerably greater than the preconsolidation pressure. The difference in the two curves is believed to be related to the different magnitude of shear stresses developed between the soil particles during isotropic and anisotropic consolidation. However, the important point is that the difference is probably one of soil structure and therefore does not affect the validity of the effective stress theory for saturated soils. The

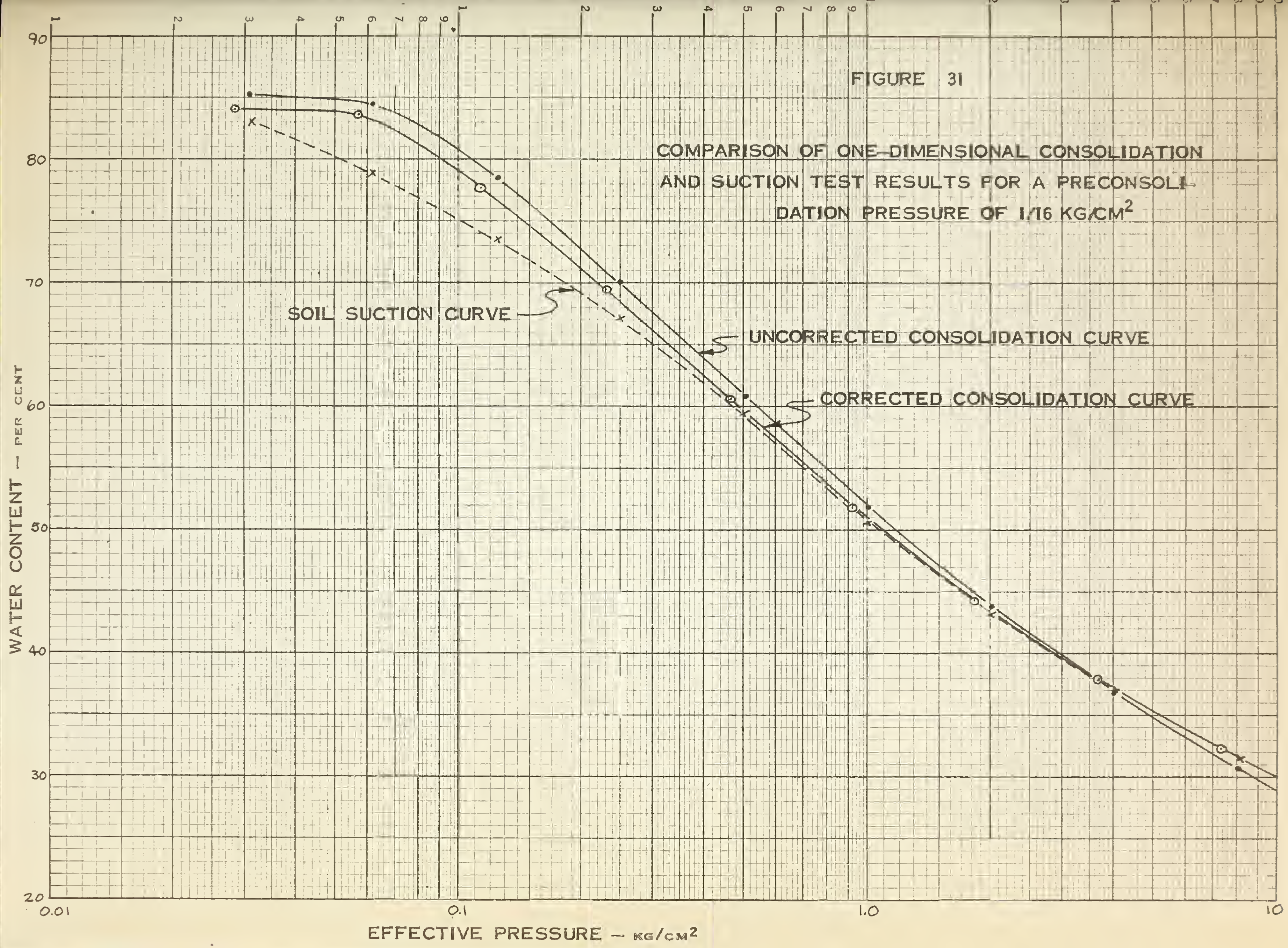


FIGURE 31
COMPARISON OF ONE-DIMENSIONAL CONSOLIDATION AND SUCTION TEST RESULTS FOR A PRECONSOLIDATION PRESSURE OF 1/16 KG/CM^2
SOIL SUCTION CURVE
UNCORRECTED CONSOLIDATION CURVE
CORRECTED CONSOLIDATION CURVE
WATER CONTENT — PER CENT
EFFECTIVE PRESSURE — KG/CM^2

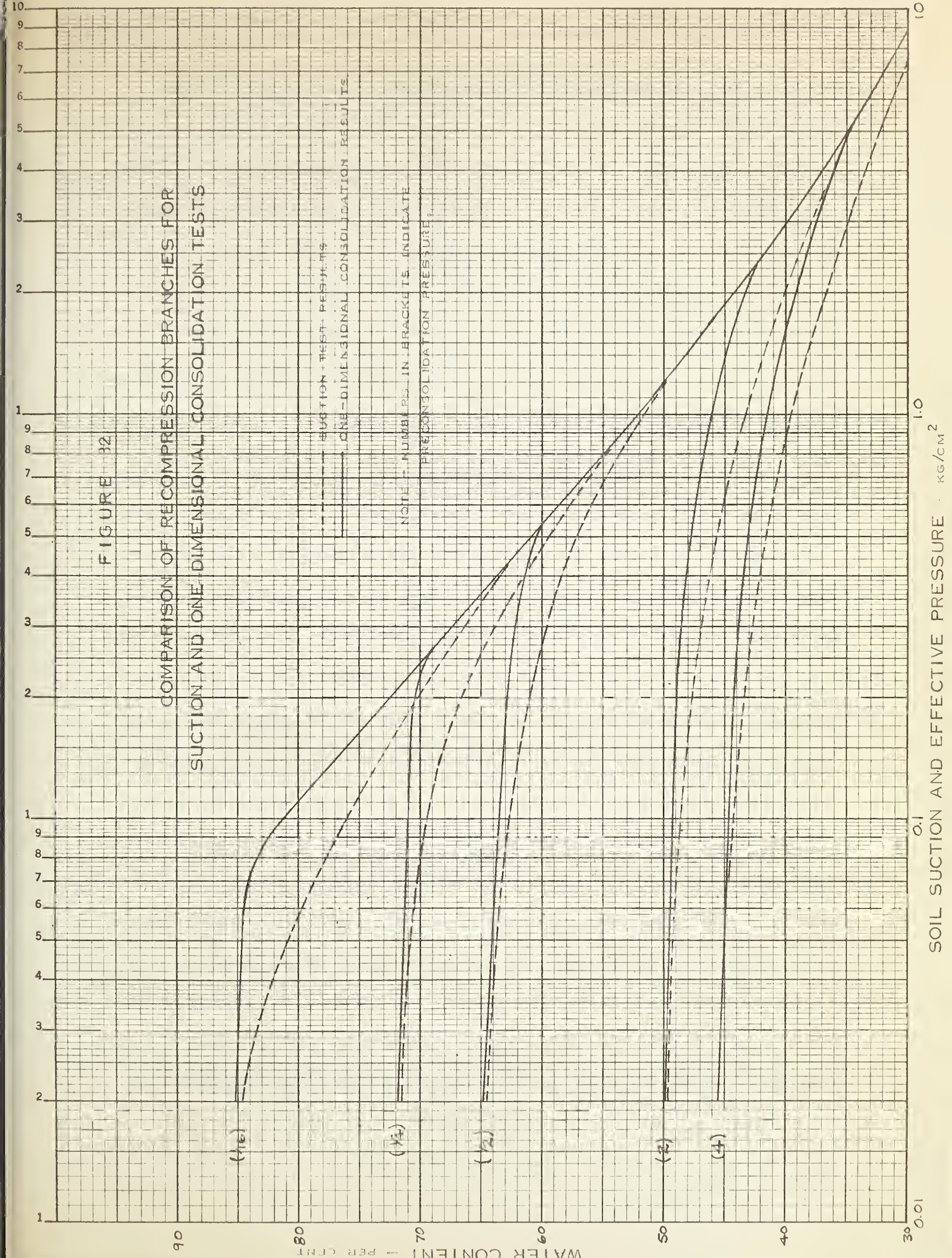


FIGURE 32

COMPARISON OF RECOMPRESSION BRANCHES FOR SUCTION AND ONE DIMENSIONAL CONSOLIDATION TESTS

difference between the recompression branches of the two types of consolidation results may also be related to the side friction acting upon the soil in the one-dimensional consolidation test. During the rebound of a sample, the developed side friction is related to the passive pressure of the soil and then upon subsequent recompression it is related to the active pressure of the soil. Whether this stress reversal has an appreciable effect upon the shape of the recompression branch cannot be definitely stated at this time.

Jennings (1960) and Aitchison (1960) proposed that a point would be reached where the suction and consolidation results separate. This point was felt to coincide with the commencement of air entry into the sample. FIGURES 13 and 14 show that the degree of saturation starts to decrease at approximately the plastic limit and greatly decrease at water contents approaching the shrinkage limit. The one-dimensional consolidation tests decrease the water content to only 30 per cent, a water content in excess of the point where desaturation commences. However, it can be predicted that the curves should commence to diverge at a water content of approximately 25 per cent, with the one-dimensional consolidation curve going below the suction curve. Terzaghi's conventional effective stress equation for a 2-phase system will not hold beyond this point since the soil in the suction test is in a 3-phase system. The most widely accepted effective stress equation for a three-phase system can be written as follows:

$$\sigma' = \sigma + \chi(u_a - u_w) - u_a$$

The parameter χ has been widely accepted and means the same as the para-

meter ψ used by Bishop and Aitchison, and β used by Croney and Jennings.

The above equation for the effective stress relationship of partially saturated soils becomes equal to Terzaghi's conventional equation when the system is saturated since χ becomes 1.0. The factor χ is the ratio of the effective stress in the soil to the stress in the water phase. It should be noted that the suction test measures the stress in the water phase of a soil. Therefore, it would appear possible to use the conventional consolidation test in conjunction with the suction test to investigate the behavior of partially saturated soils.

On the basis of the results from the testing program, it appears that Terzaghi's equation for effective stresses holds true for the suction test when the soil is saturated. Since desaturation commences at lower suction values for low plasticity soils, it should be noted that the range over which the suction and one-dimensional consolidation coincide would be much less. However, it can be stated that as long as the soil remains saturated, the results of the suction and one-dimensional consolidation tests are essentially the same.

Referring to the analysis previously reviewed for the prediction of heave, it appears that both methods have essentially the same relationship for predicting the final equilibrium conditions up to the point where desaturation of the soil commences. In clay soils, the two methods would probably be synonymous for most cases encountered in the field.

7:7 Factors Affecting Rate of Consolidation in the Suction and the One-Dimensional Consolidation Test

The factors which affect the rate of consolidation of a soil

are discussed first in this section. Then the laboratory results are analysed in an attempt to determine whether or not it is possible to apply Terzaghi's theory of consolidation to the suction test in a similar manner to which it is applied to the conventional one-dimensional consolidation test. The method used for the analysis of the results involves the application of the consolidation theory to the suction test results and if they agree with the one-dimensional test results, the theory can be said to apply. In order to perform such an analysis it is necessary to eliminate or equate as many factors as possible.

The factors affecting consolidation may be first divided into two groups, those associated with the properties of the soil and those resulting from the test procedure or precesses encountered during the test. Physical properties of the soil affecting consolidation are as follows:

(1) Void Ratio - Previously in this thesis it was shown that the equilibrium void ratio (or water content) conditions were the same for both the suction and the one-dimensional consolidation tests on the virgin compression branch. On the recompression branch there was a difference in equilibrium conditions and for this reason only time consolidation curves from the virgin compression branch are used for comparison. Therefore, the void ratio variable should be eliminated if time consolidation curves for similar pressure increments are compared.

(2) Coefficient of Compressibility, a_v - This factor is a direct measure of the slope of a pressure versus void ratio curve and since the virgin compression branches are the same for the two tests under question, this

variable is eliminated when similar pressure increments are considered.

(3) Permeability - The calculation of permeability from consolidation test results involves the use of the time consolidation curve and since it is the time consolidation characteristics which are being studied it is of no avail to calculate permeabilities in order to find out if they are the same in both types of tests. However, it is important to realize the factors which affect permeability. Taylor (1948) outlines these factors as (i) grain size (ii) properties of the pore fluid (iii) void ratio (iv) shapes and arrangements of pores and (v) undissolved gas within the pore water. The first factor of grain size can be eliminated since the same soil was used for both tests. The properties of the pore fluid should also be the same for both tests. The suction and the one-dimensional consolidation tests were performed in the same room at the same time which should equate the effects of temperature. The shape and arrangement of the soil particles is not definitely known and can only be postulated. Since the suction test is essentially a 3-dimensional consolidation process and the conventional consolidation test is a one-dimensional consolidation process there may be a slightly different structure developed in the sample. It should be noted that all samples were initially consolidated one-dimensionally from a slurried condition to various densities in which it is most probable that a flocculated* structure existed. The samples which were removed from the consolidation rings and placed in the suction apparatus were subjected to 3-dimensional consolidation which should cause them to retain essentially a flocculated structure. Samples continuously consolidated one-dimensionally would tend to develop a dispersed* structure. Seed (1959) showed that the permeability of a

soil may vary considerably depending upon its structure. For example, a sandy clay at a dry density of 118 lbs per cubic foot was found to vary in permeability from 10^{-7}cm per second in a dispersed state to 10^{-5}cm per second in the flocculated state. Although the difference in structure occurring in the suction and one-dimensional consolidation test may not be of similar magnitude to that mentioned above, it is interesting to note that structure has a considerable effect upon permeability. Mathematically it may be written that permeability is proportional to the degree of flocculation in the soil structure. Therefore, it would appear that the permeability of the soil in the suction test would be higher than that in the one-dimensional consolidation test.

The factor of undissolved gases in the pore water should not be of significance. However, it should be noted that in the one-dimensional consolidation, the degree of saturation increases during the test and approaches 100 per cent while in the suction test it is initially about 97 per cent saturated and decreased to approximately 93 per cent at the end of the test. Thus, the degrees of saturation at the end of both tests would differ by about 7 per cent. Lambe (1951) shows that an increase in degree of saturation shows a corresponding increase in permeability. For example, the premeability for a sandy material is found to increase from 4.2×10^{-4} to 5.2×10^{-4}cm per second when the degree of saturation is changed from 93 to 100 per cent. In 1954, Lambe stated, "The influence of degree of saturation on permeability is minor in comparison with composition, structure and void ratio."

(4) Length of Drainage Path - The amount of consolidation occurring at any time is directly proportional to the square of the length of the

drainage path. Since all samples under consideration in both tests have different lengths of drainage paths it appears reasonable that all results should be reduced to one common length. It must be understood that the length of drainage path is a difficult measurement to determine accurately and that any error encountered is squared in the calculation. Measurements of length of drainage path in the suction test where especially difficult and this may be the explanation for some of the scatter in results.

There may be factors affecting the rate of consolidation which are the result of the technique by which the test is run or the result of the actual consolidation process which occurs in the sample when the suction load is applied. For example, in the one-dimensional consolidation test the time consolidation characteristics depend upon the pressure increment and the length of time each increment is allowed to act. These factors in all probability affect the suction test results to a certain degree, however, no literature was encountered dealing with the rate of consolidation in a suction test. It may also be possible that the menisci at the surface of the sample in some way affect rate of consolidation. Also the fact that the total stress remains constant throughout the process of consolidation may effect the rate of consolidation. The above statements are only postulated and it is the purpose of the interpretation of test results to point out whether or not these occur and are of significance.

7:8 Comparison of Rate of Consolidation Test Results

FIGURE 19 shows the agreement which exists between the suction

test experimental results and the theoretical time consolidation curve. The curve was fitted at 50 per cent consolidation and was found to deviate somewhat but is still felt to be within the limits of error which could be expected. However, it should be noted that the one-dimensional results (FIGURE 23) are in closer agreement with the theoretical curve. These curves were not corrected for compressibility of filter paper because the agreement was extremely close, however, corrections would make the curves lie directly on top of each other down to a point in excess of 90 per cent consolidation. Secondary consolidation exists in the suction results but it may not occur to the same extent as in the one-dimensional consolidation results. It is difficult to make a definite statement as to the differences in secondary consolidation in the two types of tests since the suction tests were not carried far enough onto the secondary consolidation branch. An estimate of the average value for the slope of the secondary compression branch for the suction test is 0.23 cm^3 and 0.32 cm^3 for the one-dimensional consolidation tests. The differences in slope of the secondary compression branch can probably be explained on the basis of the difference in structure resulting from one-and three-dimensional consolidation. The steeper slope of the one-dimensional results is due to the slow dissipation of shear stresses in the water films around the soil particles. These shear stresses are smaller in the suction test and result in a smaller slope of the secondary compression branch.

Although the theoretical consolidation curve fits the suction test results reasonably well, it does not necessarily prove that the soil property which is a measure of the rate of consolidation is the

same for both tests. The coefficient of consolidation is a property which depends upon the physical constants of a soil affecting the rate of volume change. FIGURES 20 and 24 show coefficient of consolidation results of suction and one-dimensional consolidation tests respectively. Limited results are available for the suction test with considerable scatter occurring in the results shown. The coefficient of consolidation is dependent upon a large number of factors and is known to be difficult to reproduce in the laboratory. Part of the scatter occurring on FIGURE 20 can be explained by inaccurate determination of the length of drainage path which was assumed to be equal to the approximate thickness of the sample. Data from the best-fit line through results can be tabulated as follows.

TABLE II

COEFFICIENT OF CONSOLIDATION (cm^2/sec)

PRESSURE kg/cm^2	SUCTION TEST	ONE-DIMENSIONAL CONSOLIDATION TEST
0.1	1.15×10^{-4}	0.90×10^{-4}
0.4	0.50×10^{-4}	0.85×10^{-4}
1.0	0.20×10^{-4}	0.76×10^{-4}

There appears to be a definite difference in the results of the two types of tests but it is difficult to visualize the behavior of this quantity. For clarity it was felt advantageous to plot pressure versus time to 50 per cent consolidation rather than the coefficient of consolidation. Theoretical confirmation of this plot is shown by the

following relationships.

$$C_v = \frac{k\ (1 + e)}{a_v\ \gamma_w}$$ where C_v is calculated from the

relationship, $$C_v = \frac{T_x\ h^2}{t_x}.$$

where C_v = coefficient of consolidation

k = coefficient of permeability

a_v = coefficient of compressibility

T_x = theoretical time factor to any per cent consolidation

t_x = actual time to a corresponding per cent consolidation

h = length of drainage path

Equating the above relationships gives,

$$\frac{T_x\ h^2}{t_x} = \frac{k\ (1 + e)}{a_v\ \gamma_w}$$

or

$$t_x = \frac{T_x\ h^2\ a_v\ \gamma_w}{k\ (1 + e)}$$

Assuming T_{50}, a_v, γ_w, $(1 + e)$ the same for both types of tests, t_{50} varies directly as h^2 and inversely as k. For the present, permeability will also be assumed equal for both types of tests and its effect will be studied later. If all times to 50 per cent consolidation are corrected to one length of drainage path and plotted against pressure, the factors under consideration should be more easily visualized. FIGURE 33 shows a plot of t_{50} versus effective pressure with all t_{50} values corrected to a drainage length of one centimeter. Best-fit line data is shown in TABLE III.

FIGURE 33

CORRECTED TIME TO 50 PER CENT CONSOLIDATION IN THE ONE-DIMENSIONAL CONSOLIDATION AND SUCTION TESTS VERSUS EFFECTIVE PRESSURE

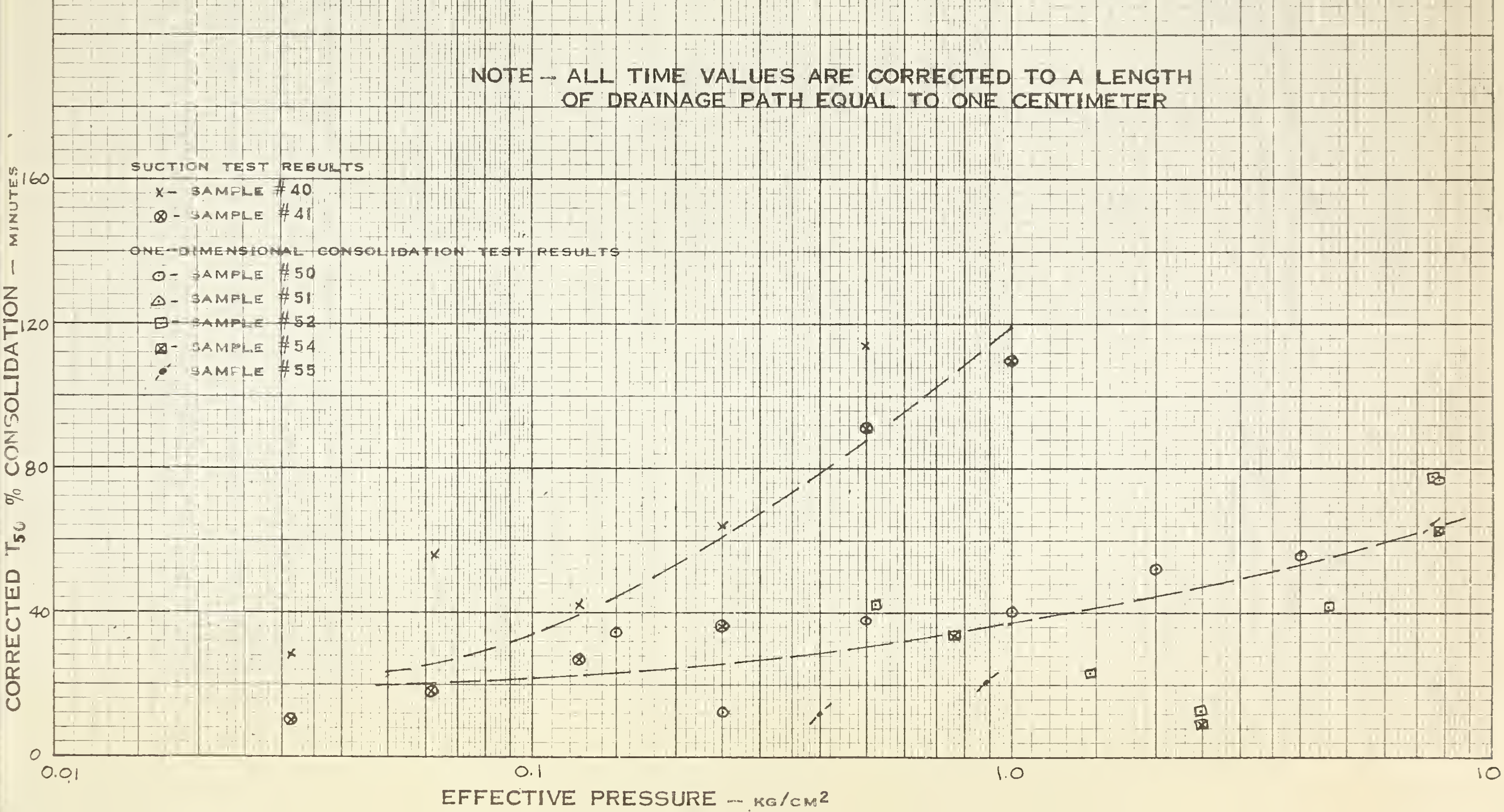


TABLE III

TIME TO 50 PER CENT CONSOLIDATION WHEN h = 1 cm. (MINUTES)

EFFECTIVE PRESSURE kg/cm^2	SUCTION TEST	ONE-DIMENSIONAL CONSOLIDATION TEST
0.1	35	22
0.4	80	32
1.0	120	38

The above results show that at low effective pressures (or high void ratios) the time to 50 per cent consolidation for both types of tests differ less than at high effective pressure (or low void ratios). At a pressure of 1 kg/cm^2 the time required for 50 per cent consolidation is 3 times as long in the suction test as in the one-dimensional consolidation test. The only soil properties which could be responsible for this are those related to permeability. If the soil is assumed to have a more flocculated structure in the suction test, the permeability would be higher than that of the one-dimensional consolidation test and would mean less time should be required for 50 per cent consolidation by the suction method. Such is not the case and reasoning along that line suggests that even more difference in the results would occur if the structure variable were eliminated.

Assuming a slightly lower degree of saturation in the suction test would decrease its permeability. However, a difference of approximately 7 per cent in the degree of saturation should have only a small effect on the rate of consolidation. Scott (1963) states in the range

of degree of saturations from 80 to 100 per cent, the ratio of the unsaturated to the saturated permeability is nearly a linear function of the degree of saturation and varies as $[1 - m (1 - S/100)]$ where "m" is a constant and "S" is the degree of saturation. The constant "m" can be taken as equal to 3.5. Considering a suction of one kg/cm^2, the permeability at 100 per cent saturation would be,

$$k_{100} = k_{93} \frac{[1 - 3.5 (1 - 1.00)]}{[1 - 3.5 (1 - 0.93)]}$$

$$k_{100} = 1.32\ k_{93}$$

The time to 50 per cent consolidation would be reduced to,

$$t_{50}\ (100) = t_{50}\ (93) \frac{k_{93}}{k_{100}}$$

$$t_{50}\ (100) = 12.0 \frac{(k_{100})}{(1.32 k_{100})} = 91 \text{ minutes}$$

It is the authors opinion that degree of saturation cannot be definitely stated as the cause of the difference between the time consolidation characteristics. However, more information is necessary before this point can be proven.

There appears to be no soil property which fully accounts for the difference in time consolidation characteristics. Examination of suction test time versus volume change curves show that consolidation commences at a much slower rate than the one-dimensional consolidation test. The first portion of the curves are relatively flat for the first 5 minutes. In other words, there appears to be a time delay before consolidation commences. This time delay could be the cause for the difference in rate of consolidation characteristics. Also it should be remembered that the three-dimensional consolidation process

decreases the cross-sectional area of the sample over which drainage can occur. This may affect the rate of consolidation to an appreciable degree. However, more data is necessary before any definite statements can be made.

The importance of the rate of consolidation results with relation to the vertical ground movement problem in the field is that the rate of adjustment of the soil to climatic factors may be much less pronounced than anticipated by the conventional consolidation theory. If this is true it is very possible that analysis involving climatic factors, such as "Thornthwaite's rational classification of climate", could prove to be a useful tool in engineering practice, (Thornthwaite, 1948).

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions have been reached in this investigation.

1. A literature review revealed that the capillary analogy is most widely accepted to describe the swelling mechanism of a desiccated soil. The pore water in a desiccated soil exists in a state of tension which is termed the 'soil suction'. The addition of water to a desiccated soil mass decreases the tension stresses in the water phase and decreases the effective stress with the result that a volume increase occurs. The above mechanism is believed to apply as long as there is not a collapse of soil structure.

2. Two main analyses have been developed by investigators for the prediction of the amount of heave which might occur if an impermeable membrane is placed over the soil surface. One analysis was developed by Croney et al in England and is based on the suction test. The second analysis was developed by Jennings in South Africa, and is based on the one-dimensional consolidation test. Further research which appears to give promising results has been done by Burland on Jennings' analysis.

3. The relationship between specific bulk volume and water content are the same whether the soil is dried by evaporation or in the suc-

tion apparatus.

4. When Regina Clay is dried from a slurried condition, the soil remains saturated to a water content near the plastic limit of the soil which corresponds to a soil suction of approximately 16 kg/cm^2. At moisture contents less than the plastic limit air invasion takes place resulting in partial saturation.

5. The virgin compression branch of the suction and the one-dimensional consolidation test results are identical in the pressure range tested that is from 0.05 to 12 kg/cm^2. Therefore, the suction tests behave in accordance with Terzaghi's effective stress theory. Also, both tests give the same final equilibrium conditions when used in the analysis for the prediction of heave as long as the soil remains saturated.

6. The recompression branch of the suction test results always plots below that of the one-dimensional consolidation test results. This difference is believed to be related either to soil structure or side friction in the consolidation ring.

7. The rate of consolidation was slower in the suction test than in the one-dimensional consolidational test with the difference increasing with an increase in effective pressure. No definite reason can be given at present for the difference in the results.

The following recommendations are made for future research

1. The analyses for the prediction of heave given by Croney et al and Jennings should be applied to actual cases occurring in western

Canada in an attempt to correlate predicted and actual ground movements.

2. Further study should be given to Burland's revision of Jennings analysis since it may lead to a reasonably accurate and economical method for the prediction of vertical ground movement.

3. Prior to further research involving the suction test, it would be beneficial to do further development on the soil suction apparatus. Some essential factors which should be incorporated in the apparatus are as follows:

(i) The operating range should extend from approximately 0.1 kg/cm^2 to 15 kg/cm^2.

(ii) The volume change of the soil samples should be measurable as well as the water content change.

(iii) The rate of water content change should also be measurable.

4. Investigation should be conducted to determine the relationship between the suction and the one-dimensional consolidation characteristics for soils with varying plasticities and degrees of saturation. By using a testing program similar to that used in this thesis, it should be possible to use a combination of the two tests to study the behavior of partially saturated soils.

5. The rate of consolidation in the suction test does not appear to have been studied to any extent by previous research workers and since the results from this thesis show that the consolidation process is slower than in the one-dimensional consolidation test, it is recommended that further investigation be carried out.

6. A further investigation of the correlation between the suction test and the Atterberg limits of a soil may prove useful.

LIST OF REFERENCES

Aboshi, H., and Monden, H., "Three Dimensional Consolidation of Saturated Clays". Proc. of 5th Int. Conference of Soil Mechanics and Foundation Engineering, (1961).

Aitchison, G. D., "Relationship of Moisture Stress and Effective Stress Functions in Unsaturated Soils". Pore Pressure and Suction in Soils, London Butterworths (1960).

Aitchison, G. D., and Holmes, J. W., "Suction Profiles in Soils Beneath Covered and Uncoverd Areas". 5th Int. Conference on Soil Mechanics and Foundation Engineering, (1961).

ASTM Committee D-18 "Procedures for Testing Soils". American Society for Testing Materials, (1958).

Baracos, A., and Marantz, O., "Vertical Ground Movements". Proc. 6th Canadian Soil Mechanics Conference of the Associate Committee on Soil and Snow Mechanics, Tech. Mem. 27:29-36. (1952).

Baracos, A., and Bozozuk, M., "Seasonal Movement in Some Canadian Clays". Proc. of the 4th Int. Conference on Soil Mechanics and Foundation Engineering, London 3:264-8. (1957).

Bishop, A. W., and Henkel, D. J., "The Measurement of Soil Properties in the Triaxial Test". Edward Arnold (Publishers) Ltd. Second Edition (1962).

Black, W. P., Croney, D., and Jacobs, J. C., - "Field Studies of the Movement of Soil Moisture", - Road Research Technical Paper No. 41, Department of Scientific and Industrial Research, Road Research Board, (1958).

Buckman, H. O., and Brady, N. C., "The Nature and Properties of Soils". McMillan Company (1962).

Burland, J. B., "The Estimation of Field Effective Stress and the Prediction of Total Heave using a Revised Method of Analyzing the Double Oedometer Test". Die Sivielle Ingenieur in Suid-Afrika, (July, 1962).

Capper, P. L., and Cassie, W. F., "The Mechanics of Engineering Soils"; 3rd Revised Edition, London W.C. 2, (1961).

Cooling, Dr. L. F., Discussion on papers presented under the heading "General Principles and Laboratory Measurements", Pore Pressure and Suction in Soils, Butterworths (1960).

Cooling, M. L. F., Aitchison, M. D. D., Jennings, M. J. A., Discussion on "Expansion and Shrinkage of Non-Saturated Soils". Proceedings of the 5th Int. Conference of Soil Mechanics and Foundation Engineering (1961).

Croney, D., and Coleman, J. D., and Bridge, P. M., "The Suction of Moisture Held in Soil and Other Porous Materials". Road Research Tech. Paper No. 24, London (H. M. Stationary Office) (1952).

Croney, D., and Coleman, J. D., "Soil Moisture Suction Properties and Their Bearing on the Moisture Distribution in Soils". Proceedings of the 3rd Int. Conference on Soil Mechanics and Foundation Engineering (1953).

Croney, D., Coleman, J. D., and Black, W. P. M., "Movement and Distribution of Water in Soil in Relation to Highway Design and Performance". Water and Its Conduction in Soils, Highway Research Board, Special Report #40, (1958).

Croney, D., and Coleman, J. D., "Pore Pressure and Suction in Soil". Pore Pressure and Suction in Soils, London Butterworths (1961).

Denesson, N. J., Tok Chum, J. Y., Burland, J. B., Demons, N. E., and Williams, A. A. B., discussion on "The Heaving of Buildings and The Associated Economic Consequences with Particular Reference to the Orange Free State Goldfields". The Civil Engineer in South Africa, (May, 1963).

D. S. I. R. "Soil Mechanics for Road Engineers". Road Research Laboratory HMSO, (1952).

Gardner, W. R., "Soil Suction and Water Movement". U. S. Salinity Laboratory. Pore Pressure and Suction in Soils, London Butterworths (1961).

Gilbert, O. H., Jr. "A Device for Measuring Tensions in Water", Highway Research Board, Bulletin 245, (1960).

Habib, P., "Contribution a la Mesure Des Pressions Interstitielles".

Pore Pressure and Suction in Soils, London, Butterworths (1961).

Haefeli, R., and Amberg, G. "Contributions to the Theory of Shrinking". Proceedings of 2nd Int. Conference on Soil Mechanics and Foundation Eng. Vol. 1. (1948)

Hamilton, J. J., 1962, "Volume Changes in Undisturbed Clay Profiles in Western Canada". Canadian Geotechnical Journal, Vol. 1., No. 1, (1963).

Hardy, R. M., Brooker, E. W., and Curtis, W. E., "Landslides in Over-Consolidated Clays", The Engineering Journal (1962).

Hardy, R. M., "Note in Theoretical Soil Mechanics". University of Alberta, Edmonton, Alberta (1963)

Jennings, J. E. B., and Knight, K., Discussion by G. W. Donaldson and C. M. A. de Bruijn to "The Prediction of Total Heave from the Double Oedometer Test". Symposium on Expansive Soils, Trans. of the South African Institution of Civil Engineers (1957).

Jennings, J. E., "A Revised Effective Stress Law For Use in the Prediction of the Behavior of Unsaturated Soils". Proceedings of the Conference on Pore Pressure and Suction in Soils, Butterworths, London (1960).

Jennings, J. E. and Kerrich, J. E., "The Heaving of Buildings and The Associated Economic Consequences, with Particular Reference to the Orange Free State Goldfields". Die Sivielle Ingenieur in Suid-Afrika, (November 1962).

Jumikis, A. R., "Soil Mechanics". D. Van Vostrand Co., Inc., Princeton, New Jersey (1962).

Lambe, W. T., "Soil Testing for Engineers". John Wiley & Sons, Inc., New York (1951).

Lambe, W. T., "The Permeability of Fine-Grained Soils". Symposium on Permeability of Soils. ASTM Special Technical Publication No. 163, (1954).

Lambe, W. T., & Whitman, R. V., "The Role of Effective Stress in the Behavior of Expansive Soils". Quarterly of the Colorado School of Mines, Vol. 54, No. 4, Golden, Colorado,(1959).

Leonards, G. A. & Girault, P., "A Study of One-Dimensional Consolidation Test". 5th International Conference on Soil Mechanics and Foundation Engineering (1961).

Matlock, H., & Dawson, R. F., "Aids in the Interpretation of the Consolidation Test". Symposium on Consolidation Testing of Soils. Special Technical Publication No. 126, ASTM (1951).

NRC "Building Research 1962", National Research Council of Canada, Div. of Building Research, NRC 7659, Ottawa, (1963).

NRC Unpublished information from the files of National Research Council, Division of Building Research, Saskatoon, Saskatchewan, (1964).

Penner, E., "Soil Moisture Suction - Its Importance and Measurement". NRC, Ottawa Technical Paper No. 76 (1959)

Peterson, R., & Perers, N., "Heave of Spillway Structures on Clay Shales". Canadian Geotechnical Journal, Vol. 1, No. 1, (1963).

Polonsky, M., "A Problem of Foundation on Loamy Soil in Sub-Tropical Countries". Proc. Ind. Int. Conference Soil Mechanics and Foundation Engineering, 4, pp78 - 81 (1948).

Raymond, G. P., "A Simple Pore Water Pressure Gauge". Advance copy of a paper to be presented at the Symposium on "Laboratory Shear Testing of Soils", at Ottawa, (1963).

Richards, L. A., & Fireman, M., "Pressure Plate Apparatus for Measuring Moisture Sorption and Transmission by Soils". Soil Science (1943).

Richards, L. A., "Methods of Measuring Soil Moisture Tension", Soil Science (1949).

Russam, K., "The Distribution of Moisture in Soils at Overseas Airfields". Road Research Tech. Paper No. 58. (1962).

Scott, R. F., "Principles of Soil Mechanics". Addison Wesley Publishing Co., Inc., Reading, Massachusetts, (1963).

Seed, H. B., "A Modern Approach to Soil Compaction". University of California, Berkeley, Eleventh Calif. Street & Highway Conference. Jan. (1959).

Seed, H. B., Woodward, R. J., & Lundgren, R., "Prediction of Swelling Potential for Compacted Clays". American Society of Civil Engineers. Vol. 128, Paper No. 3501, (1963).

Staple, W. J., "Hysteresis Effects in Soil Moisture Movement". Canadian Journal of Soil Science. Ottawa, Ontario (Dec. 1961).

Taylor, D. W., "Fundamentals of Soil Mechanics". John Wiley & Sons, Inc., London (1948).

Terzaghi, K., "Theoretical Soil Mechanics", John Wiley & Sons, (1934).

Terzaghi, K., & Peck, R. B., "Soil Mechanics in Engineering Practice", John Wiley & Sons, Inc., New York, London (1960).

Thomson, S., "Salt Content, Cations and Shear Strength", Doctrate Thesis at the University of Alberta, (Unpublished) (1963).

Thornthwaite, C. W., "An Approach Toward a Rational Classification of Climate", Geographical Review 38, (1948).

Wooltorton, F. L. D., "The Scientific Basis of Road Design". Edward Arnold Ltd., (1954).

APPENDIX A

EXAMPLES OF HEAVING OCCURRING TO BUILDINGS

- Eston Elementary School
- Industrial Warehouse, Regina

APPENDIX A

EXAMPLES OF HEAVING STUDIES BY THE WRITER

A:1 Introduction

Several examples of the effects of swelling clays on structures were studied by the writer during his employment with the National Research Council of Canada. This appendix outlines the extent of the problem encountered in two locations in Saskatchewan. Often the magnitude of the problem is not properly perceived and it is hoped that these examples will place a better perspective on the problem.

A:2 Eston Elementary School

Details of this example were obtained from the files of the Division of Building Research, NRC, at Saskatoon, Saskatchewan (1964). Eston is located about 100 miles southwest of Saskatoon, Saskatchewan. As well as being in an area with a highly plastic clay soil, it is subject to arid climatic conditions. There was much evidence in this area of the heaving problem.

The old elementary school in Eston was built in 1924 and since that time there has been considerable work done on the building to cope with heaving of the structure. Damage to the exterior load-bearing wall was moderate while extensive movement had occurred on the lightly loaded basement floors. The maximum total movement of the floor has been in excess of thirty inches. Differential movement of the exterior wall had not caused severe damage while the interior load bearing partitions showed more serious damage. The maximum differential movement on the first floor

was in excess of five inches. A semi-basement area of the school has caused the most difficulty. This area has a wooden floor system and heaving has occurred to the extent that the floor has been lifted and relaid at least three times during the life of the building. It is also in need of being replaced again. At each time of repair, the maximum differential heave has been in the order of eight inches. Repairs included excavation of a large quantity of soil, replacing the concrete surface footings upon which the wooden floor joists are supported, and then replacing the flooring.

Factors noticed at the site which could have contributed to a greater or lesser degree to the increase in moisture beneath the building can be listed as follows: inadequate provision to carry away roof drainage from the eaves-troughing downspouts, and a possibility of leakage from cisterns and sanitary sumps beneath the basement level. During the past few years there has been a measured increase of more than 15% in the water content profile at an "open-field" location near the building. Probably the most surprising feature about the movements is that they have persisted at seemingly the same rate over the forty year life of the building, and the equilibrium soil moisture conditions do not appear to have been reached to date.

A:3 Industrial Warehouse, Regina

The second example deals with the heaving of the floor of an industrial warehouse in Regina, Saskatchewan. Details of this problem have recently been published in "Building Research 1962" (1963) and are quoted here.

"During the summer of 1962 an interesting case of severe heaving of a grade floor slab in a single-storey industrial warehouse in Regina was

encountered. Vertical ground movement gauges, building movement points a deep bench mark, and a neutron moisture meter access tube had been installed during construction of the building in the late summer of 1961, and readings had been taken periodically since installation. By the middle of August 1962, a maximum heave of 3.5 in. had developed in the central portion of the slab and above the centreline of a construction trench in which subfloor plumbing had been placed. This heave resulted in a maximum angular distortion of 1/30, or 1 in. in 2.5 ft., and created serious damage to interior partitions and problems for materials handling equipment. It was feared that damage to the superstructure could result if interior load-bearing partitions or the reinforced concrete grade beams were lifted off the cast-in-place concrete pile foundation.

The high temperature of the floor slab at the point of maximum heave indicated that a hot water leak had developed in the plumbing system, and excavation proved this to be true. The trench backfill, which consisted of a pit-run sandy gravel, facilitated migration of water along its length; to a lesser extent the pit-run gravel subgrade aided in further movement of water under the slab. A check on water consumption for the building showed that an increase of some 7500 gal or 1200 cu. ft., over normal usage had occurred during the period in which heaving had been observed. This represented approximately 6 in. of water over the entire area affected. Before plumbing repairs were completed the gravel subgrade had become fully saturated; the neutron moisture meter indicated an average increase in soil moisture above construction conditions of 10 per cent in the top 2 ft. of natural soil underlying the gravel fill, 5 per cent in the next foot, and a 2 per cent average increase over the next 5 ft. The rebound gauges, in-

stalled at various depths below the slab, indicated a vertical dimension change in the soil of 5 per cent in the top 2 ft., 3.33 per cent in the next foot, and 1.25 per cent over the next 5 ft."

Since the time of the above publication, the owner of the factory has done no work on the floor other than patching the hole made to repair the plumbing. Only a slight additional heave has taken place during the past year as the excess soil moisture has been redistributed to give an almost constant water content versus depth profile. Continued measurements are being taken by NRC at this location.

APPENDIX B

PROCEDURES FOR THE PREDICTION OF HEAVE

- Croney et al's Analysis

- Jennings' Analysis

APPENDIX B

PROCEDURES FOR THE PREDICTION OF HEAVE

B:1 General

Chapter IV contains a brief description of the analyses for the prediction of heave developed by Croney et al and Jennings. This appendix gives a more detailed outline of the steps involved in each analysis. Jennings original method is presented herein although subsequent to his first publication there has been considerable criticisms and revisions made by other investigators (Burland, 1962).

B:2 Croney et al's Analysis

Briefly, the analysis involves the determination of the present soil conditions in terms of a water content profile, and an estimation of the final equilibrium water content conditions from a soil suction versus water content curve.

Let us suppose the example of an airport runway placed on a highly plastic clay which has a water table located 20 feet below ground surface. The soil above the water table exists in a state of desiccation prior to construction but after the runway is completed, evaporation is inhibited and heaving of the runway results. Construction materials are assumed to apply a load of 150 pounds per square foot and have an equal pressure distribution down to the water table. The following steps are taken:

1) The equilibrium effective pressure is estimated by the formula

$$\sigma' = \gamma z - \gamma_w \ (z-H)$$

(γ is assumed for the first approximation).

2) Convert the effective pressure to the same terms used in the suction test plots. Note should be made that the soil suction values obtained in the laboratory test are assumed to be effective pressures, and equal to the final equilibrium effective pressures occurring in the field. By this reasoning large values of soil suction are recorded for the soil at the water table when in actuality, the soil suction is zero by definition.

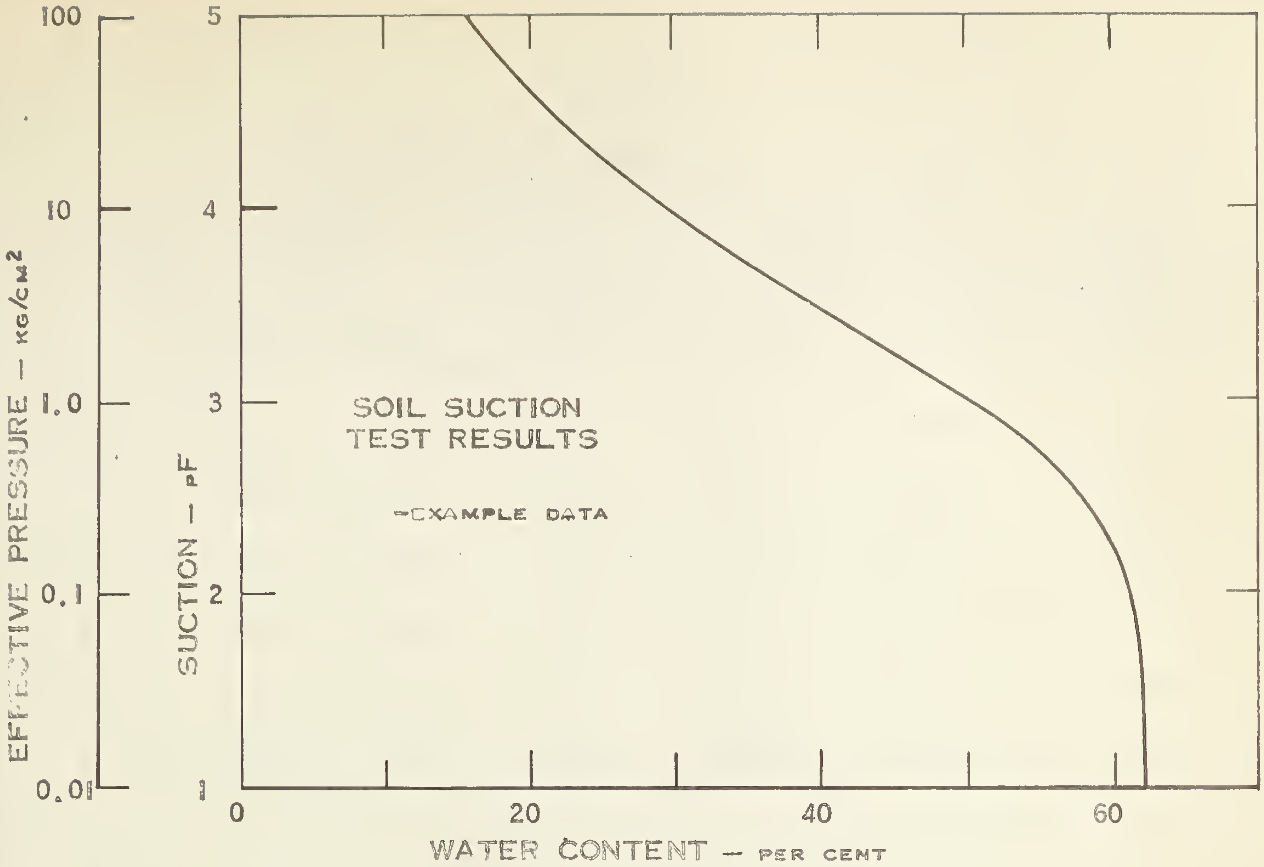
3) Use the relationship between moisture content and soil suction (effective stress) to estimate the moisture-content distribution with depth. FIGURE B.1.

4) A second approximation can be made using a bulk density which takes the water content of the soil into consideration. Tabulation of results for the above steps (with reference to the problem under consideration) are recorded in TABLE B.1.

5) The change in volume due to a change in water content can be obtained from a plot of the specific bulk volume versus water content for the soil. FIGURE B.1.

6) The per cent linear strain in the vertical direction is calculated for each increment of depth from the change in specific bulk volume (S.B.V.) divided by three times the original S.B.V. The value of 3 is used as an approximation to convert volumetric change to lineal strain.

7) The per cent lineal strain is multiplied times the thickness of the layer under consideration to give the change thickness. The accumulation of changes in thickness for each increment of depth gives an estimate of the total heave.



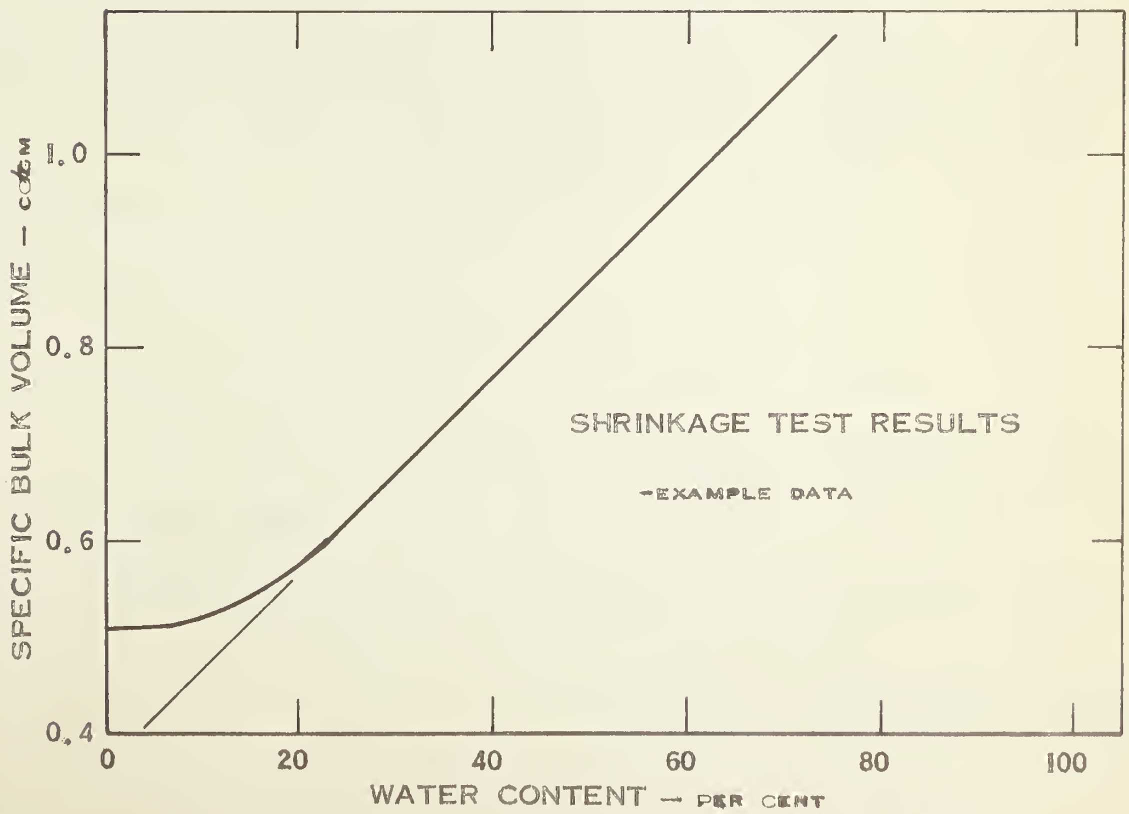


FIGURE B.1 DATA NECESSARY FOR CRONEY ET AL'S ANALYSIS

TABLE B.1

ESTIMATED EQUILIBRIUM MOISTURE DISTRIBUTION

Depth (feet)	Effective Pressure		First Approximation of Water Content (%)	Corrected Effective Pressure		Second Approximation of Water Content (%)
	lbs/ft^2	Kg/cm^2		lbs/ft^2	Kg/cm^2	
0	1398	0.682	53.2	1398	0.682	53.2
4	1588	0.775	52.3	1693	0.826	51.7
8	1779	0.868	51.3	1990	0.971	50.3
12	1969	0.961	50.5	2291	1.12	49.2
16	2160	1.05	49.7	2594	1.27	48.1
20	2350	1.15	49.0	2900	1.42	46.9

TABLE B.2

MOVEMENT OF PAVEMENT DUE TO CHANGE IN WATER CONTENT OF SOIL

Depth (feet)	Initial Water Content (%)	Final Water Content (%)	Initial Specific Bulk Volume (cc/gm)	Final Specific Bulk Volume (cc/gm)	Change in Specific Bulk Volume (cc/gm)	Linear Strain = $\frac{\text{S.B.V.}}{3(\text{S.B.V.})}$ (%)	Heave = Lineal Strain Times Depth Increment (Inches)
0	47.0	53.2	0.839	0.899	0.060	2.38	0.57
4	47.0	51.7	0.839	0.884	0.045	1.79	0.86
8	47.0	50.3	0.839	0.871	0.032	1.27	0.61
12	47.0	49.2	0.839	0.859	0.020	0.79	0.38
16	47.0	48.1	0.839	0.849	0.010	0.40	0.19
20	47.0	46.9	0.839	0.838	--	--	--

Total Heave = 2.61

B:3 Jennings' Analysis

Considering the previous problem, an estimate of heave is made in accordance with Jennings' original analysis. The soil existing in the profile above the water table is subjected to an applied vertical pressure proportional to the overburden.

$$P_o = \gamma z$$

Referring to the curves obtained from the double oedometer test, (FIGURE B.2), the void ratio associated with the applied pressure is shown on the natural water content consolidation curve as (P_o, eo). Placing a load ($\triangle P$) on the surface gives an additional vertical pressure which can be assumed to be dissipated with depth in accordance with the Theory of Elasticity. However, the following example shows it as distributed uniformily with depth for ease in calculations. If the moisture content regime is assumed to not be disturbed, the new soil conditions may be represented by the point ($P_o + \triangle P$, e_1).

However, the covering of the soil surface prevents evaporation and results in the establishment of a new moisture content regime. Jennings and Knight (1957) felt that the equilibrium conditions defined by Croney may never be quite reached in practice. However, they were unable to give a more accurate estimate of equilibrium conditions so they resorted to the same expression as that used by Croney et al.

Swelling accompanies the establishment of new equilibrium conditions which can be represented on the free swell consolidation curve by the point (P_o + u, e_2). The effect of the applied load must also be considered which gives rise to the point (P_o + u + $\triangle P$, e_3). The amount of vertical movement for the various conditions mentioned above can be calculated by summing the void ratio changes over the whole profile. It is possible

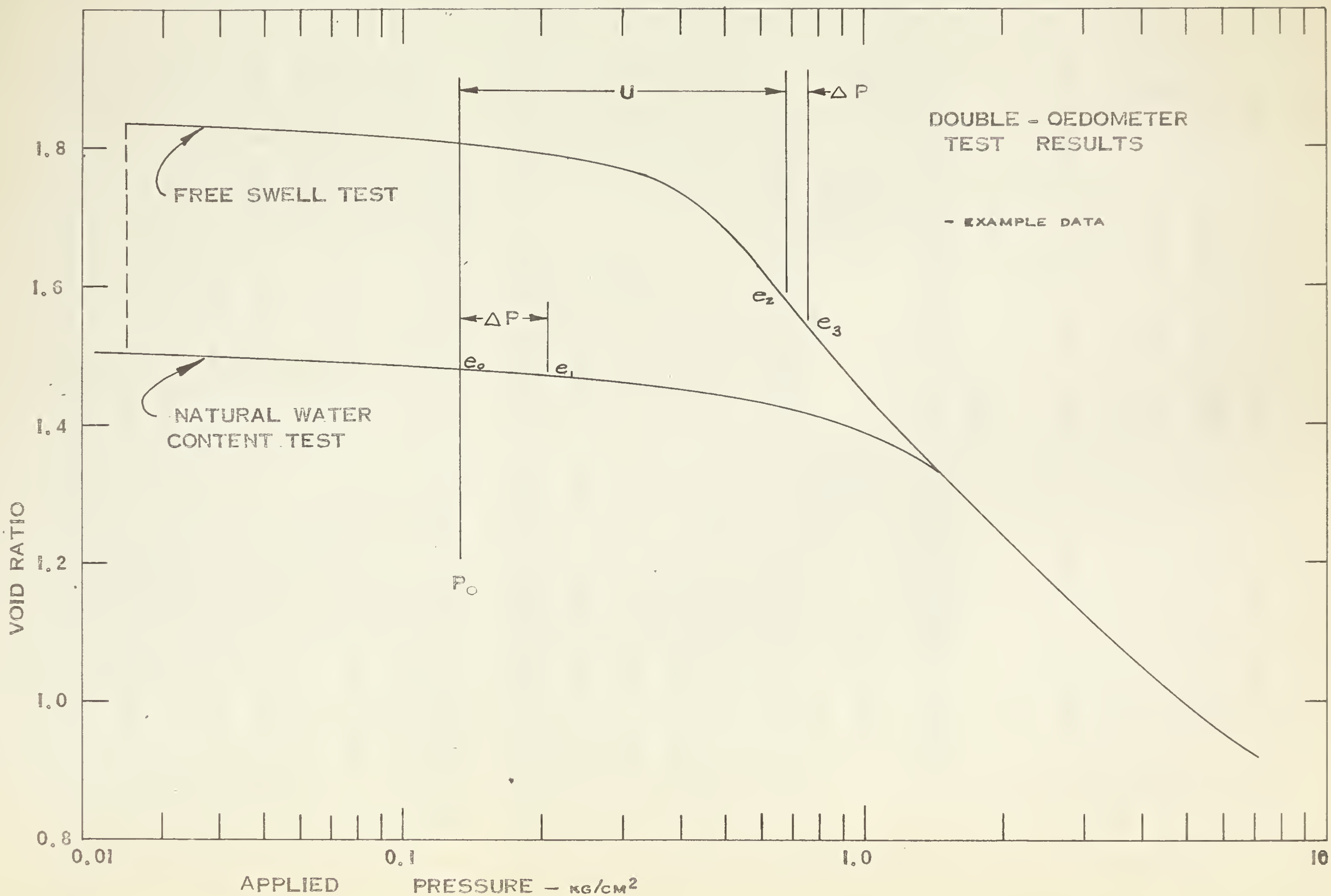


FIGURE B.2 TEST DATA NECESSARY FOR JENNINGS' ANALYSIS

to estimate (1) the amount of heave of the unloaded surface due to an accumulation of moisture (2) the settlement due to the weight of the runway assuming the moisture regime is not disturbed, and (3) the net heave under the runway due to an accumulation of moisture. The necessary calculations for an analysis of the above problem are tabulated in TABLES B.3 and B.4.

TABLE B.3

PRESSURES AND CORRESPONDING VOID RATIOS FOR JENNINGS' ANALYSIS

Depth (feet)	Po at Mean = γz Depth		ΔP	u at Mean Depth Kg/cm^2	Void Ratios			
	lbs/ft^2	Kg/cm^2	Kg/cm^2		e_o	e_1	e_2	e_3
0	272	0.133	0.073	0.548	1.482	1.473	1.575	1.540
4	818	0.399	0.073	0.427	0.452	1.445	1.510	1.482
8	1368	0.668	0.073	0.305	1.427	1.420	1.410	1.430
12	1920	0.937	0.073	0.183	1.399	1.390	1.410	1.390
16	2475	1.21	0.073	0.061	1.363	1.352	1.375	1.353

Burland (1962) gives an approximate method to determine the effective stresses in a natural water content consolidation test and goes on to show how this curve can be used in the prediction of heave. Burland criticizes Jennings' plot of the double oedometer test results on the basis that both effective and applied stresses are shown on the same scale. Also, the natural water content consolidation test does not give the true picture of the effective pressures in the field. There has been widespread use of the double oedometer test in South Africa which has resulted in the correlation of predicted and actual heave (Burland, 1962). The predicted values

TABLE B.4

MOVEMENT OF PAVEMENT DUE TO LOADING AND/OR COVERING

Depth	Heave of unloaded surface $= \frac{H}{1 + e_o}(e_o - e_2)$ (inches)	Settlement under weight of runway $= \frac{H}{1 + e_o}(e_o - e_1)$ (inches)	Net heave under runway $= \frac{H}{1 + e_o}(e_o - e_3)$ (inches)
0	1.80	0.17	1.12
4	1.14	0.14	0.59
8	0.53	0.14	0.06
12	0.22	0.18	0.18
16	0.24	0.22	0.20
Total	3.93	0.85	1.39

are larger than the actual heave and Burland believes this is due to the incorrect application of the double oedometer test results.

The above analysis appears to be a very practical tool to use in connection with the design of foundations for buildings. The author feels that further study should be made into the application, the more recent modifications and developments of the analysis.

APPENDIX C

SOIL SUCTION TEST EQUIPMENT

- Methods of Measuring Soil Suction
- Pressure Plate Extractor
- Pressure Membrane Extractor
- New Pressure Plate Apparatus

APPENDIX C

SOIL SUCTION TEST EQUIPMENT

C:1 Introduction

This appendix includes summaries of equipment development by other research workers and the details concerning equipment used in this thesis which may be of benefit if further research is carried out in this field. Literature pertinent to this thesis has been written in many parts of the world and also be investigators in fields other than engineerings. As well, several techniques were developed by the author which make the testing procedures more reliable and it is felt that this record may prevent duplication if further research is performed on this topic.

C:2 Methods of Measuring Soil Suction

The principles of soil suction measurement have been thoroughly studied by agricultural research workers. Several methods are given below along with the pressure range to which they apply and a short note on their operation. The reference following the note gives the publication in which a full description may be found.

TABLE C.1

Methods of Soil Suction Measurement

Method	Range (kg/cm^2)	Remarks
Suction Plate	0 to 0.8	A sample is placed in contact with a porous

.....Table continued

TABLE C.1 (Cont'd)

Methods of Soil Suction Measurement

Method	Range (kg/cm^2)	Remarks
		disc and allowed to come to equilibrium with an applied suction to the water below the disc. The equilibrium water content is measured by weighing the wet weight of the sample. This procedure is repeated for various applied suctions to determine the complete soil suction versus water content relationship. (Croney et al, 1952).
Continuous Flow	0 to 0.8	The amount of moisture moving to and from the sample is metered with a glass tube. (Croney et al, 1952).
Rapid Method	0 to 0.8	Permits the actual measurement of suction in a sample. The suction applied is adjusted so no change in water content occurs in the soil sample (Croney et al, 1952).
Pressure Plate	0 to 1	Air pressure is applied above the porous stone on which the specimen rests, while the water beneath the stone is at atmospheric pressure (Richards et al, 1943).
Field Tensiometer	0 to 0.8	A porous stone, inserted into the soil is connected to either a mercury monometer or a bourdon gauge to measure the tension in the water phase (Black et al, 1958).

.....Table continued

TABLE C.1 (Cont'd)

Methods of Soil Suction Measurement

Method	Range (kg/cm^2)	Remarks
No flow tensiometer to be used with triaxial apparatus	0 to 6	The soil is placed in contact with a fine-grained ceramic stone, which is connected by a closed water system to a flexible steel membrane. Tension is controlled by externally adjusting the membrane deflection. The absence of a free water surface prevents cavitation (Gilbert, 1950).
Capillary Manometer		A thermometer operating on the basis of Boyles Law is used to measure the suction in soil samples. The thermometer is connected either to an hypodermic needle which can be put into the sample or directly to a triaxial cell (Raymond, 1963; Habib, 1960).
Pressure Membrane	0.1 to 20	This device extends the range of the pressure plate to a higher soil suction range. A cellulose membrane on which the sample rests is supported by metal mesh containing water at atmospheric pressure (Croney et al, 1958).
Centrifuge	1 to 30	The technique applies a high constant gravitational field to a soil supported on a porous stone with a fixed water table at its base. Suction is a square root function of the speed of rotation (Croney et al, 1952).

.....Table continued

TABLE C.1 (Cont'd)

Methods of Soil Suction Measurement

Method	Range (kg/cm^2)	Remarks
Freezing Point Depression	1 to 10	It is possible to deduce the suction by measuring the freezing point depression of a soil sample. However, results are affected by the supercooling of the soil water (Croney et al, 1952).
Gypsum Block (Electrical resistance gauges)	0.5 to 50	The electrical resistance of an absorption type material varies with the tension on the pore water. Gauges require detailed calibration and are affected considerably by the salt content of the soil.
Vacuum Desiccator	100 to 10,000	Small samples of soil are allowed to reach equilibrium with known relative humidity conditions. Constant relative humidity can be obtained by sulphuric acid solutions or salt slurries. Evacuation of desiccator accelerates equilibrium (Croney et al, 1952).
Sorption Balance	100 to 10,000	Vapor pressure is measured directly with respect to a vacuum by an oil manometer. The samples are weighed on a Joly spring balance and considerable accuracy can be obtained.

Description of other soil suction measuring devices appear in the literature but most of them are only variations and modifications of the types already mentioned.

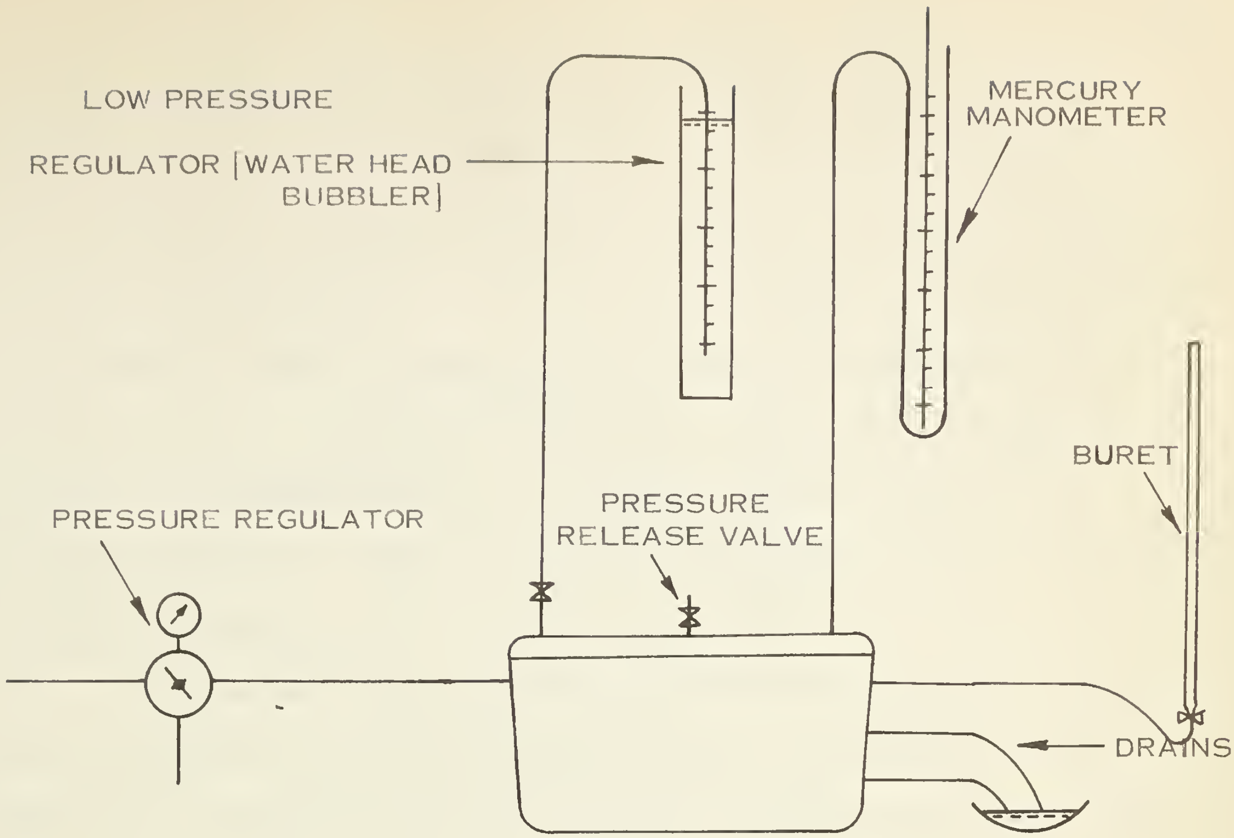
C.3 Pressure Plate Extractor

The pressure plate extractor (Cat. No. 1200) is produced by Soilmoisture Equipment Company, Santa Barbara, California, and can be purchased through Soiltest Incorporated (FIGURE C.1). It is designed to remove water from soil samples in the 0 to 1 kg/cm^2 soil suction range. This is accomplished by special ceramic plates operating in a pressure chamber. Prepared soil samples are placed on the wetted ceramic plate of the pressure plate cell, mounted in the pressure chamber and subjected to air pressure. The fine pores in the ceramic plates form water menisci at the air-water boundary which prevent air from passing through the plates. A pressure applied to the chamber removes water from a soil sample until equilibrium is reached, at which point the water in the sample is under a tension equal to the applied pressure.

Each of the four pressure plate cells has an air entry value (when wetted) in excess of one kg/cm^2 and a permeability which is at least 1×10^{-3} cm. per sec. Each cell consists of a ceramic plate which is sealed on one side by a thin neoprene rubber diaphragm which is kept from close contact with the ceramic plate by an appropriate internal screen. Water from the soil sample flows through the ceramic plate, then between the rubber diaphragm and the plate, and up through the outlet tube to the outside of the pressure chamber.

Clips attached to the vertical support bars form the base to rest the ceramic plates. The outflow tube is passed through the hole in the side of the pressure chamber and the rubber stopper prevents the leakage of air between the chamber wall and the outflow tube.

A pressure release valve is located in the centre of the lid.



SETUP OF PRESSURE PLATE EXTRACTOR

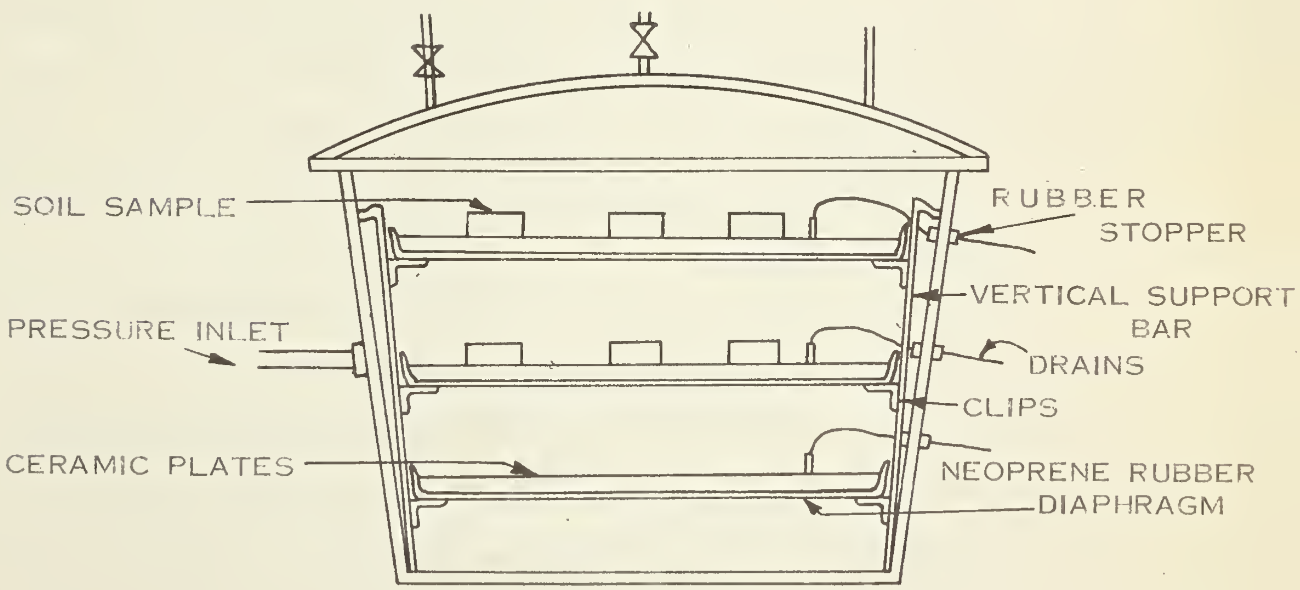


FIGURE C.1 - PRESSURE PLATE EXTRACTOR

During the testing program for this it was necessary to seal off this valve because it would not stay closed at pressures below 1/8 kg/cm^2. A mercury manometer is threaded into one of the holes in the lid to measure pressure. To the other hole in the lid was connected a constant water head pressure device. This was only used for low pressures and proved to be very satisfactory. It worked on the principle that pressures slightly in excess of the water head would be eliminated by the bubbling of air up through the water. Also it gave a much more accurate method of measuring the applied pressure.

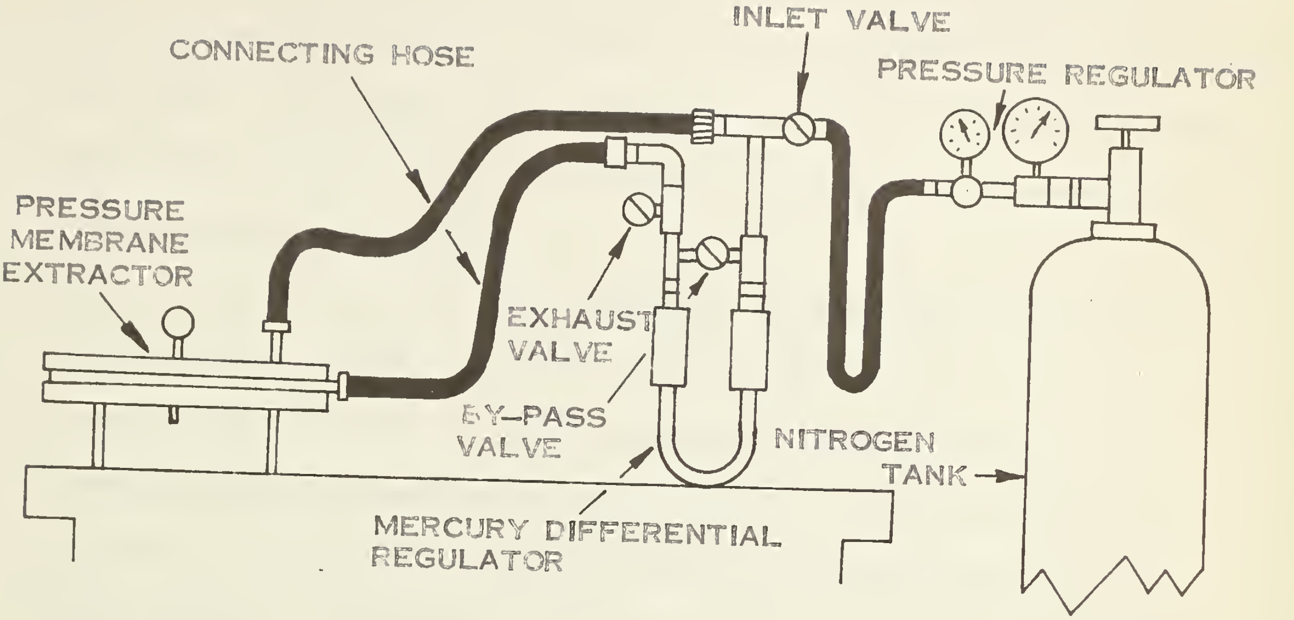
The pressure inlet, located at the back of the pressure chamber must be connected to a pressure source in excess of one kg/cm^2. Either compressed air tanks or the standard laboratory pressure line can be used.

The pressure regulator suggested by the manufacturers is the Hoke Regulator, Cat. No. 661. However, after the first set of tests were performed it was felt that pressure fluctuations were too great. For further tests a two-stage Conoflow regulator from a Bristol Recorder was used. Its sensitivity is $\pm$ 0.2 inches of water (0.0005 kg/cm^2) and no fluctuations could be noticed on the mercury manometer.

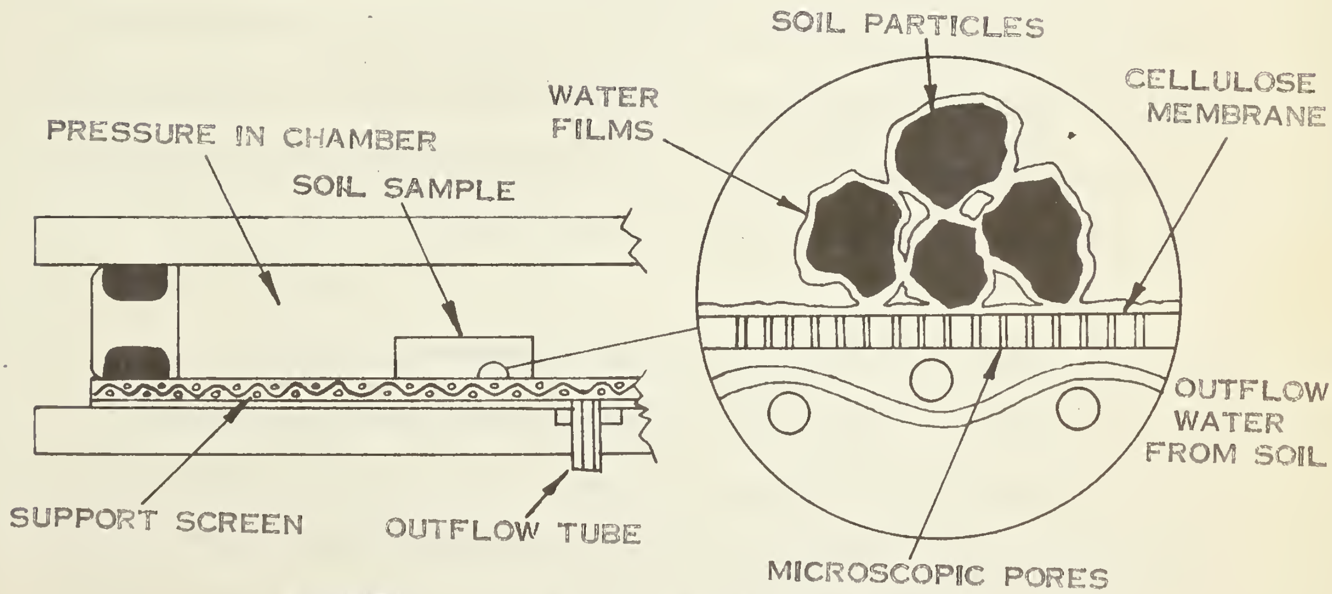
C.4 Pressure Membrane Extractor

The pressure membrane extractor (Cat. No. 1000) is produced by Soilmoisture Equipment Company and can be purchased through Soiltest Incorporated (FIGURE C.2). It is designed to remove moisture from a soil sample in the 0 to 15 kg/cm^2 soil suction range. Agricultural workers term this point the wilting point of plants.

A thin, wet, cellulose membrane supported on one side by a fine screen, is subjected to air pressure on the opposite side. Samples are placed on the wet cellulose membrane and subjected to pressure inside the



SETUP OF PRESSURE MEMBRANE EXTRACTOR



SECTION VIEW OF EXTRACTION PROCESS

FIGURE C.2 – PRESSURE MEMBRANE EXTRACTOR

extractor. The microscopic pores of the cellulose membrane are sealed to the air pressure by water menisci while water is allowed to pass through.

The air pressure in the chamber creates a condition such that water passes from the soil, through the cellulose membrane until equilibrium is reached. For example, if a pressure of 1 kg/cm^2 is applied to a sample, water flows from the sample until the water remaining in the sample is under a tension of 1 kg/cm^2.

A mercury differential regulator is connected between the extractor and the pressure regulator. The pressure on the one side of the U-tube pushed the mercury up in the opposite side of the tube until air starts to bubble through the mercury. Therefore, the pressure applied to the top of the sample is greater than that applied around the sides of the sample. A differential pressure of 4 psi is used by Agricultural workers but this was found to be large enough to deform the soil samples. For this reason the differential pressure was reduced to 2 psi. Also, thin aluminum plates were placed over the samples to prevent the corners from becoming rounded. The purpose of applying the differential pressure is to keep close contact between the soil sample and the cellulose membrane. The differential pressure is applied only after several hours of consolidation has occurred.

Compressed nitrogen at 2000 psi was used as a source of pressure. A Standard No. 511 Hoke regulator was initially used to control the pressure to the chamber but it was not a sensitive enough pressure control. Therefore, a second regulator was connected in series with the first to give better control for pressures up to 4 kg/cm^2.

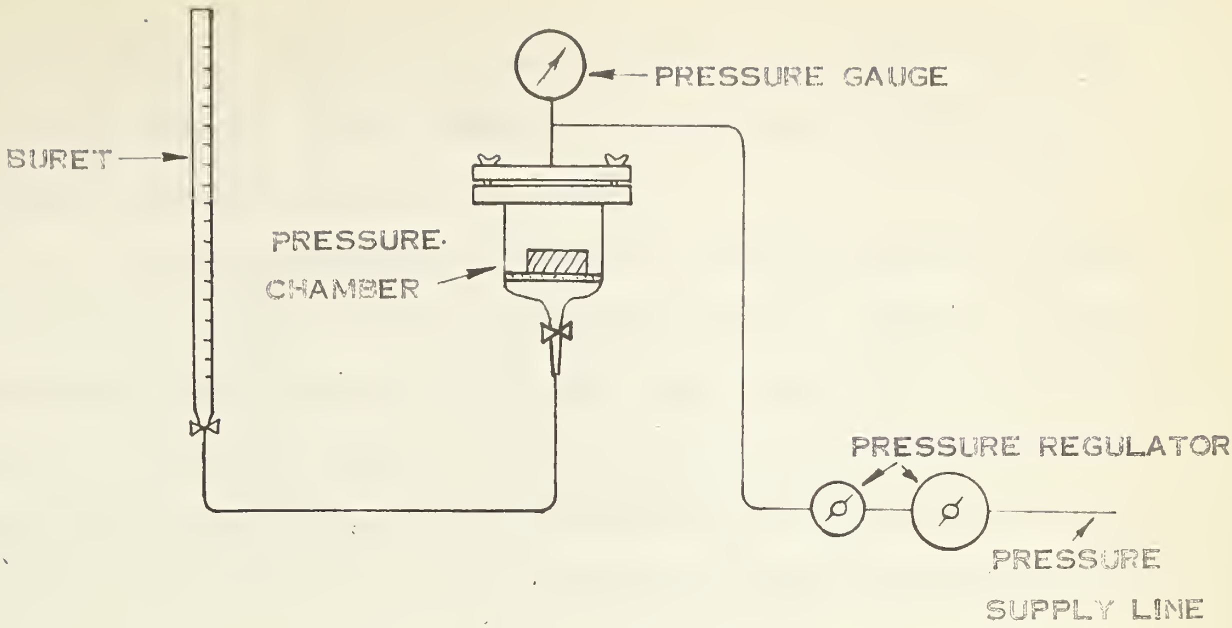
C.5 New Pressure Plate Apparatus

The pressure plate extractor used in the testing program was large, cumbersome and did not lend itself very well to research work. Therefore, it was felt necessary to develop a new piece of equipment which would overcome many of the disadvantages of the pressure plate extractor. A literature survey was first made of equipment previously developed by research workers in various parts of the world. A design similar to the pressure plate developed at the Road Research Laboratory by Croney et al (1958) appeared to be suitable.

The Division of Building Research of the National Research Council of Saskatoon supplied both technical and financial assistance in the construction of the new pressure plate apparatus (FIGURE C.3). The pressure chamber is made from a glass filter-funnel with a 6 centimeter diameter, ultra-fine porous disc. In order to study the time versus consolidation characteristics of a soil subjected to negative pore water stresses, the permeability of the porous plate must be considerably higher than that of the soil being tested. Several measurements of the permeability of the porous disc were made by measuring the rate of flow of water through it. The average of six trials gave a permeability of 2.3×10^{-7} cm. per second.

The bottom of the funnel was connected to a buret in which volume changes could be measured to the nearest hundredth of a cubic centimeter. A small polythene plug was placed in the buret which helped to make the readings more accurate and also prevented evaporation from the water surface.

A two-piece lucite cap with a rubber seal formed the top of the



SETUP OF NEW POROUS PLATE APPARATUS

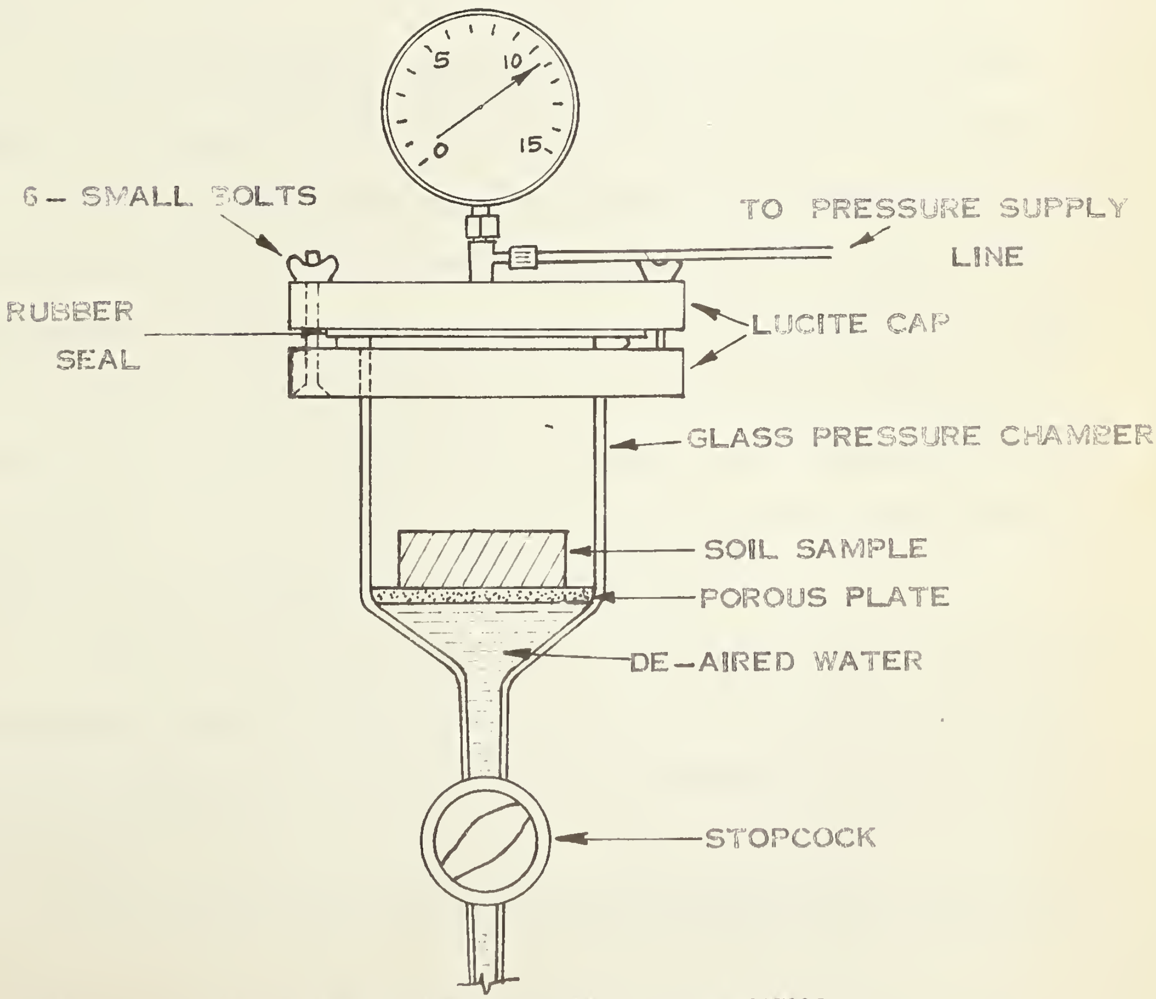


FIGURE C.3 — NEW PRESSURE PLATE APPARATUS

pressure chamber. The cap was clamped together by six small brass bolts with thumb screws. A 15 psi pressure gauge mounted on the lucite cap, measured the actual pressure in the chamber.

The constant pressure supply was initially planned to be a one-inch syringe to which various loads could be applied. However, friction and blow by around the piston introduced large errors, making it unsuitable for use. For further tests the laboratory pressure supply of 80 psi was passed through a two-stage Conoflow regulator which produced satisfactory control. The applied air pressure entered the chamber through the lucite lid.

The main advantages incorporated in the new apparatus are as follows:

1) It is compact, versatile and can be used for individual samples. For practical engineering purposes these are useful factors.

2) Since the change in water content is measured by means of a buret, it is not necessary to remove the sample from the chamber after each pressure increment. This means that the air surrounding the sample is not reduced to atmospheric pressure during the test. Errors in the pressure plate extractor due to slight rebound in the sample should now be eliminated. The test can be carried out by a procedure very similar to that of a one-dimensional consolidation test.

3) The rate of consolidation can be studied since the rate of water removal from the sample is measured. It is necessary, of course, that the permeability of the porous disc be considerably less than that of the soil.

4) It is easy to establish both the drying and wetting soil

suction curves for soils.

There are several improvements which would be useful for certain research purposes. It is difficult, however, to develop a completely versatile apparatus and thus it is often to an advantage to make special modifications to fit the particular testing program. Possible improvements can be listed as follows:

1) The buret should either be placed at a low angle of about 30 degrees to the horizontal or else made in such a way that it can be moved up and down to keep the water level in the buret equal with the level of the sample. At low pressures there may be an appreciable error in the actual chamber pressure if this is not done.

2) A mercury manometer would give more accurate measurement of the applied air pressure.

3) Of great importance for research work would be a means of measuring the volume of the specimen. This may be quite difficult to do but would be very useful for investigations into the behavior of partially saturated soils.

4) The range of the apparatus is limited to 1 kg/cm^2 and would be more useful if it were extended to about 15 kg/cm^2. In order to do this it is necessary to construct the pressure chamber of stronger material and also place a cellulose membrane over the porous plate. However, it must be remembered that it would then be impossible to study the consolidation characteristics of a soil since the permeability of the membrane would be too low.

The new pressure plate apparatus has been found to operate very well and shows good potential for use in further research.

APPENDIX D

ONE-DIMENSIONAL CONSOLIDATION TEST EQUIPMENT

- Multiplication Ratios of the Wykem-Farrance Consolidometers
- Compressibility of Apparatus and Filter Paper
- Side Friction in the Consolidation Rings

APPENDIX D

ONE-DIMENSIONAL CONSOLIDATION TEST EQUIPMENT

D:1 Multiplication Ratios of the Wykem-Farrance Consolidometers

A short testing program was conducted to determine the multiplication ratios of the three consolidometers. Measurements of the lever arms showed them to deviate from 11:1 ratio. However, difficulty was encountered in making the measurements and it was felt that a method involving the counterbalancing of weights would be more accurate. Results reveal average values as follows:

Apparatus No.	Multiplication Ratio
1	11.09
2	10.76
3	10.99

FIGURE D.1 shows the plot of pressure on the sample versus multiplication ratio for the three consolidometers. For low pressures (less than 0.04 kg/cm^2) there were fluctuations of as much as 3 1/2 per cent due to the friction in the mechanical lever arm. The above average values were used in all test result computations.

D:2 Compressibility of Apparatus and Filter Paper

A considerable amount of work was done to assess the amount and significance of the compressibility of the apparatus and the filter paper. If part of the compression registered on the dial gauge is due to the com-

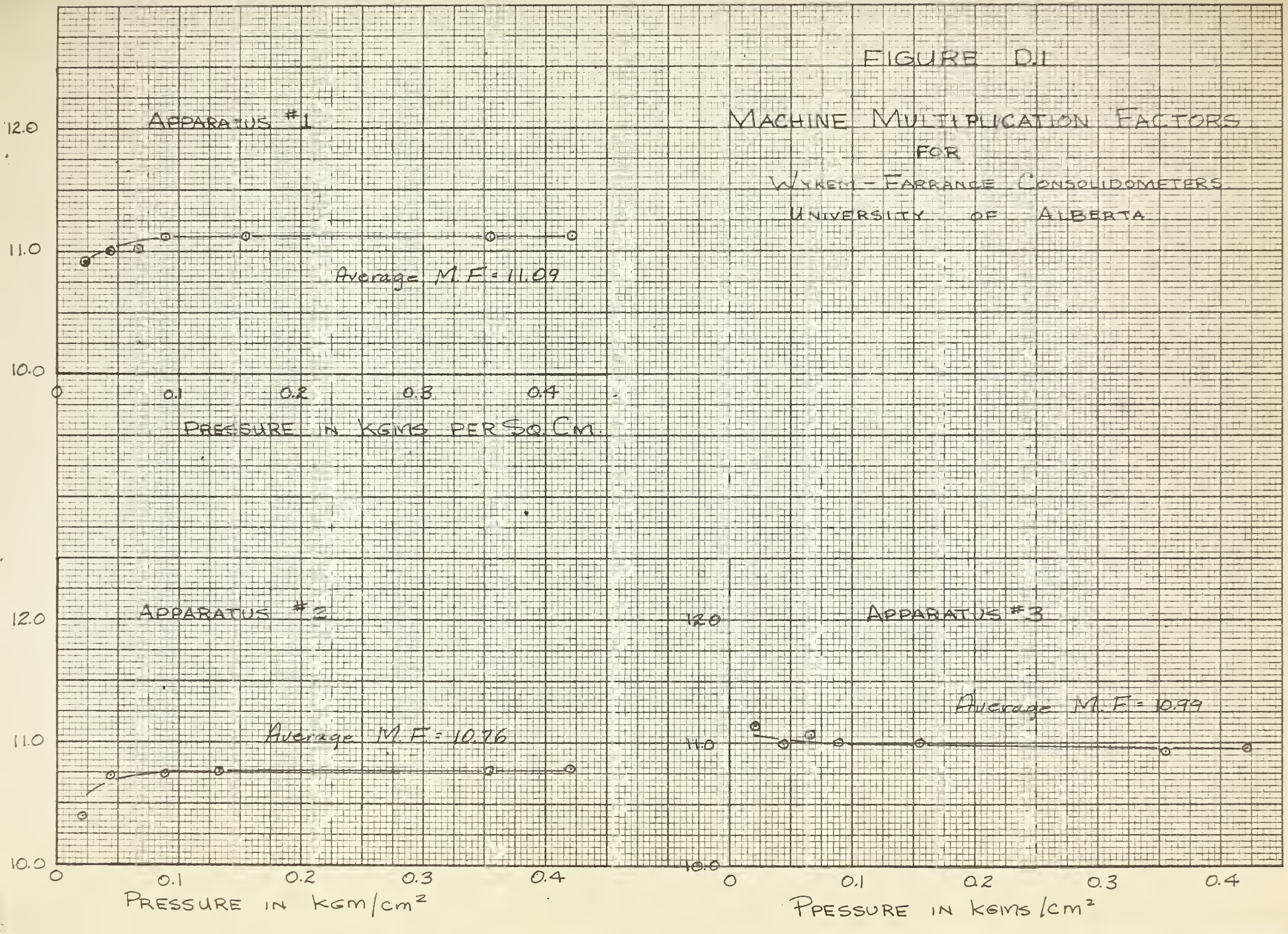


FIGURE D.1
MACHINE MULTIPLICATION FACTORS
FOR
WYKEM - FARRANCE CONSOLIDOMETERS
UNIVERSITY OF ALBERTA
APPARATUS #1
Average M.F. = 11.09
12.0
11.0
10.0
0
0.1
0.2
0.3
0.4
PRESSURE IN KGMS PER SQ. CM.
APPARATUS #2
Average M.F. = 10.76
12.0
11.0
10.0
0
0.1
0.2
0.3
0.4
PRESSURE IN KGM/CM²
APPARATUS #3
Average M.F. = 10.99
12.0
11.0
10.0
0
0.1
0.2
0.3
0.4
PRESSURE IN KGMS/CM²

pression of the apparatus and the filter paper, the true consolidation characteristics of the soil are not being measured. Usually these errors are considered insignificant but since the test results are to be compared on a more absolute basis it was necessary to attempt the assessment of correction values (Matlock and Dawson, 1951).

Compressibility of each apparatus was determined by proceeding through the loading and unloading cycle with a steel plug in the consolidometer pot. Several cycles were run on each apparatus (without any filter paper present) to check the reproducibility of compression of apparatus. FIGURE D.2 shows results from consolidation apparatus number 1. There was only a small variation from cycle to cycle for each apparatus and from one apparatus to another. Then a piece of filter paper was placed both above and below the steel plug to assimilate actual conditions during the testing procedure. The compressible nature of the filter paper made it necessary to leave each load on for a 24-hour period, similar to the procedure in the actual consolidation test. Considerable hysteresis occurred during loading and unloading of the filter paper which made it necessary to do a fairly complete testing program to assess its compression characteristics. The compressibility of filter paper was obtained by substracting the compressibility of apparatus from that of apparatus plus filter paper. As shown in FIGURE D.3, the results gives a fairly straight line on the compression pressure plot for pressures in excess of 0.1 kg/cm^2. In order that the above results be applicable in a general way to the consolidation test results, correction curves were developed which could be applied to tests performed in all three apparatuses. Since the compressibility of apparatus is less than 30 per cent of the total compression, it was felt that a best-

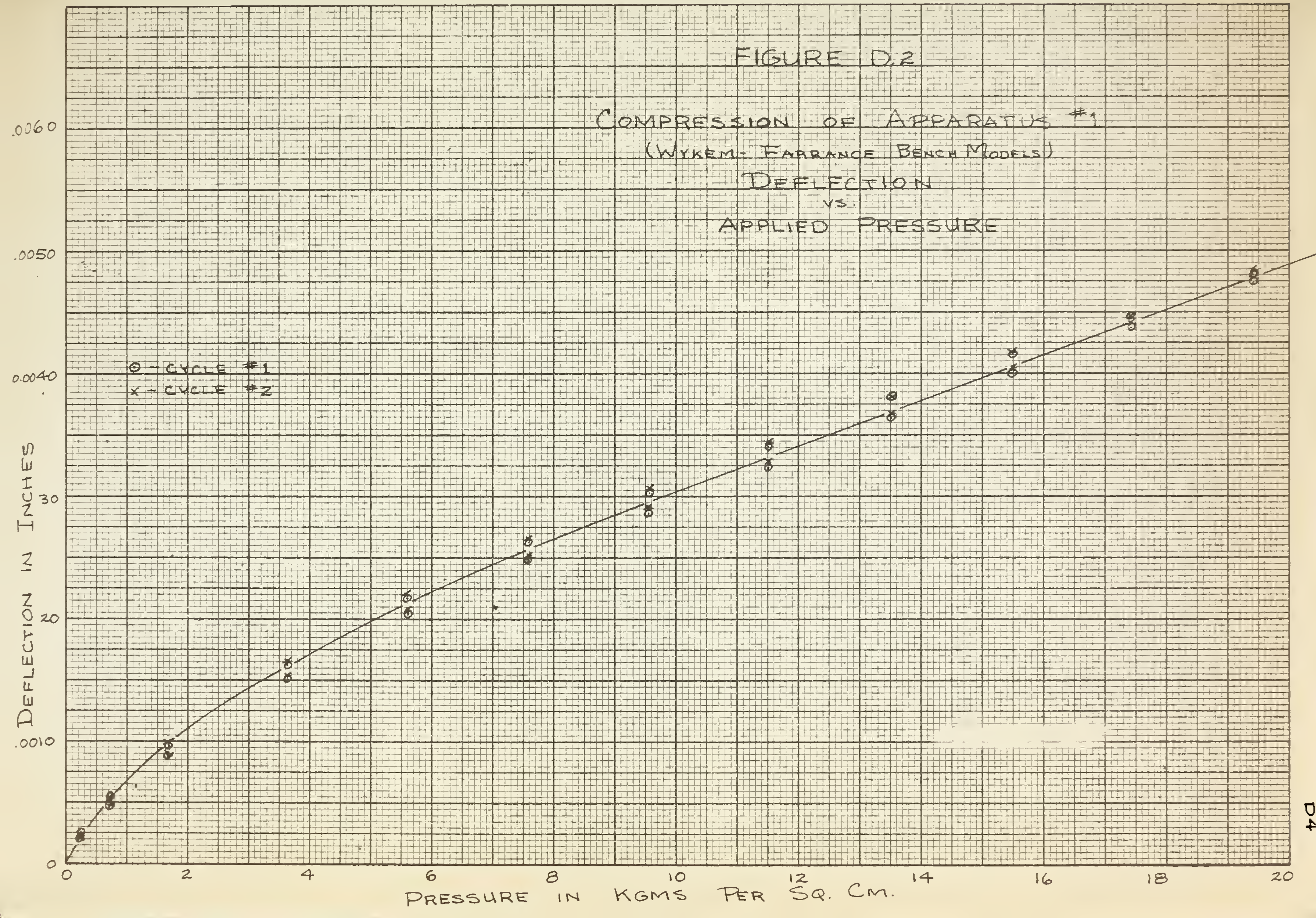


FIGURE D.2
COMPRESSION OF APPARATUS #1
(WYKEM-FARRANCE BENCH MODELS)
DEFLECTION
VS.
APPLIED PRESSURE
⊙ - CYCLE #1
x - CYCLE #2
.0060
.0050
0.0040
30
20
.0010
0
0
2
4
6
8
10
12
14
16
18
20
DEFLECTION IN INCHES
PRESSURE IN KGMS PER SQ. CM.

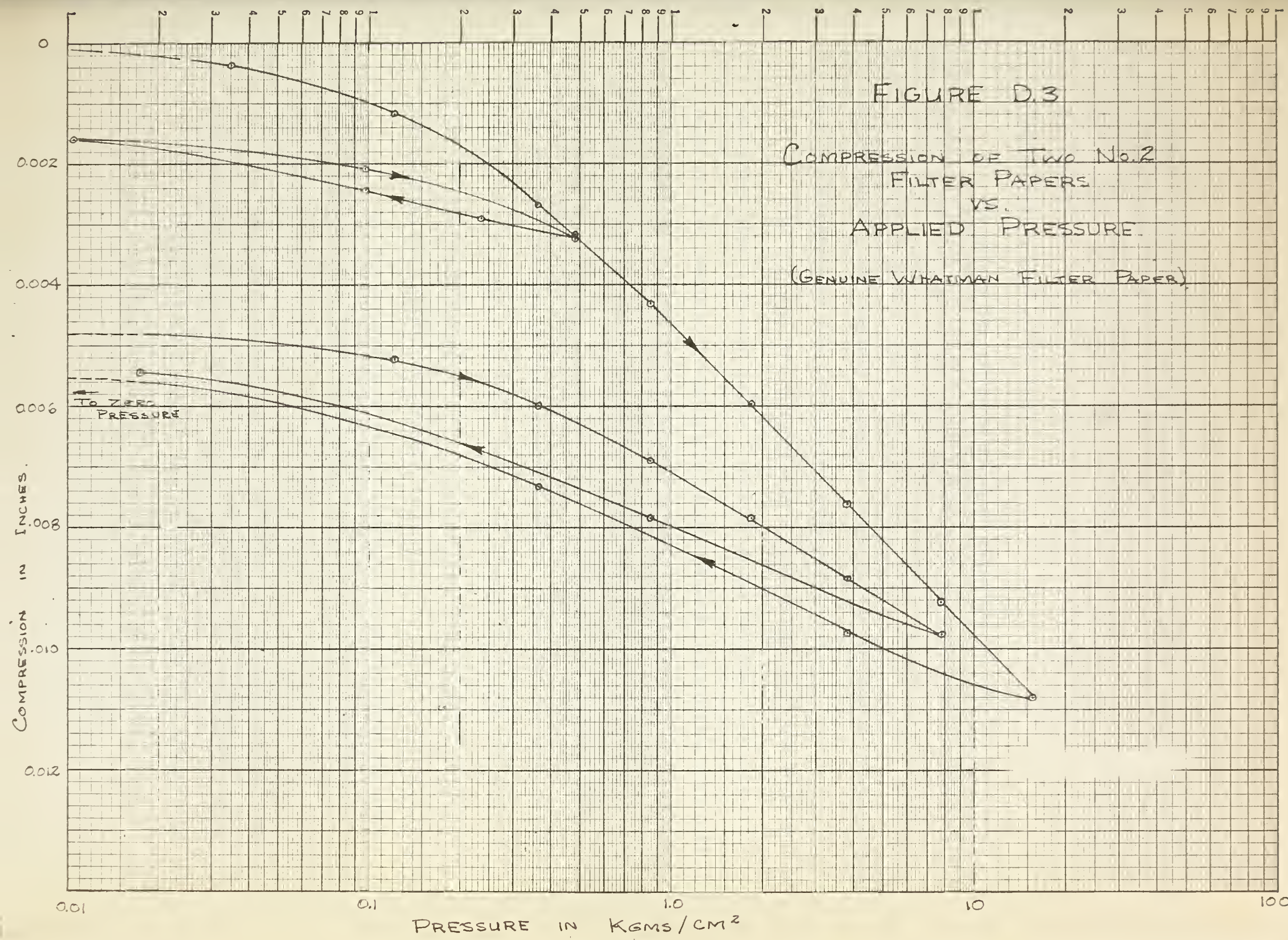


FIGURE D.3

COMPRESSION OF TWO No.2 FILTER PAPERS VS. APPLIED PRESSURE

(GENUINE WHATMAN FILTER PAPER)

fit curve could be drawn through the results without introducing much error. Also, the hysteresis due to loading and unloading of the apparatus was negligible. FIGURE D.4 shows the average compressibility of consolidometer versus log applied load.

By adding the compressibility of apparatus to that of the filter paper, a general correction curve (FIGURE D.5) was developed for the three Wykem-Farrance bench model consolidometers and two pieces of No. 2 Whatman filter paper. The complete correction curve was not determined experimentally but was extrapolated from the results shown previously.

The log time versus deflection curves showed a straight line relationship over a 24-hour period. Typical curves (FIGURES D.6) show a large initial compression and then a further gradual compression with time. Approximately six per cent of the initial drop is due to the compression of the apparatus. In analysing the filter paper compression results it was found that the time versus deflection relationship depended on both the applied load and the load increment ratio. Since the log time versus deflection plots are a straight line it is convenient to plot the slope of the line against the applied pressure for various load increment ratios. The relationship (FIGURE D.7) shows:

1) For a constant pressure increment ratio the slope increases to an optimum value and then decreases. The optimum value depends upon the load increment ratio.

2) For a constant applied pressure, the slope of the log time versus deflection curve varies directly as the pressure increment ratio.

FIGURE D.8 is a plot of log time versus deflection corrections for various applied pressures and a load increment ratio equal to one.

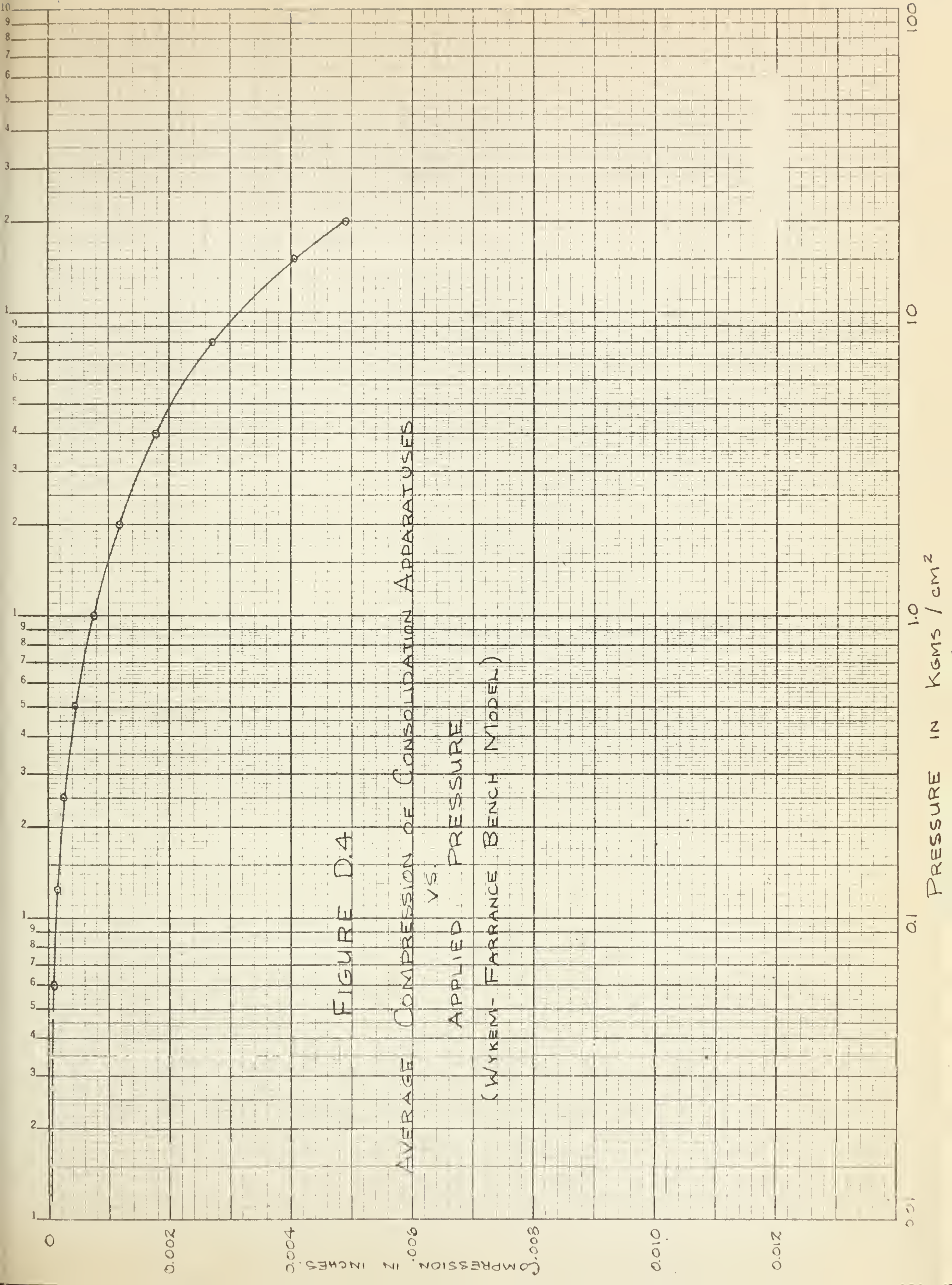


Figure D.4

Average Compression of Consolidation Apparatuses vs. Applied Pressure

(Wykem-Farrance Bench Model)

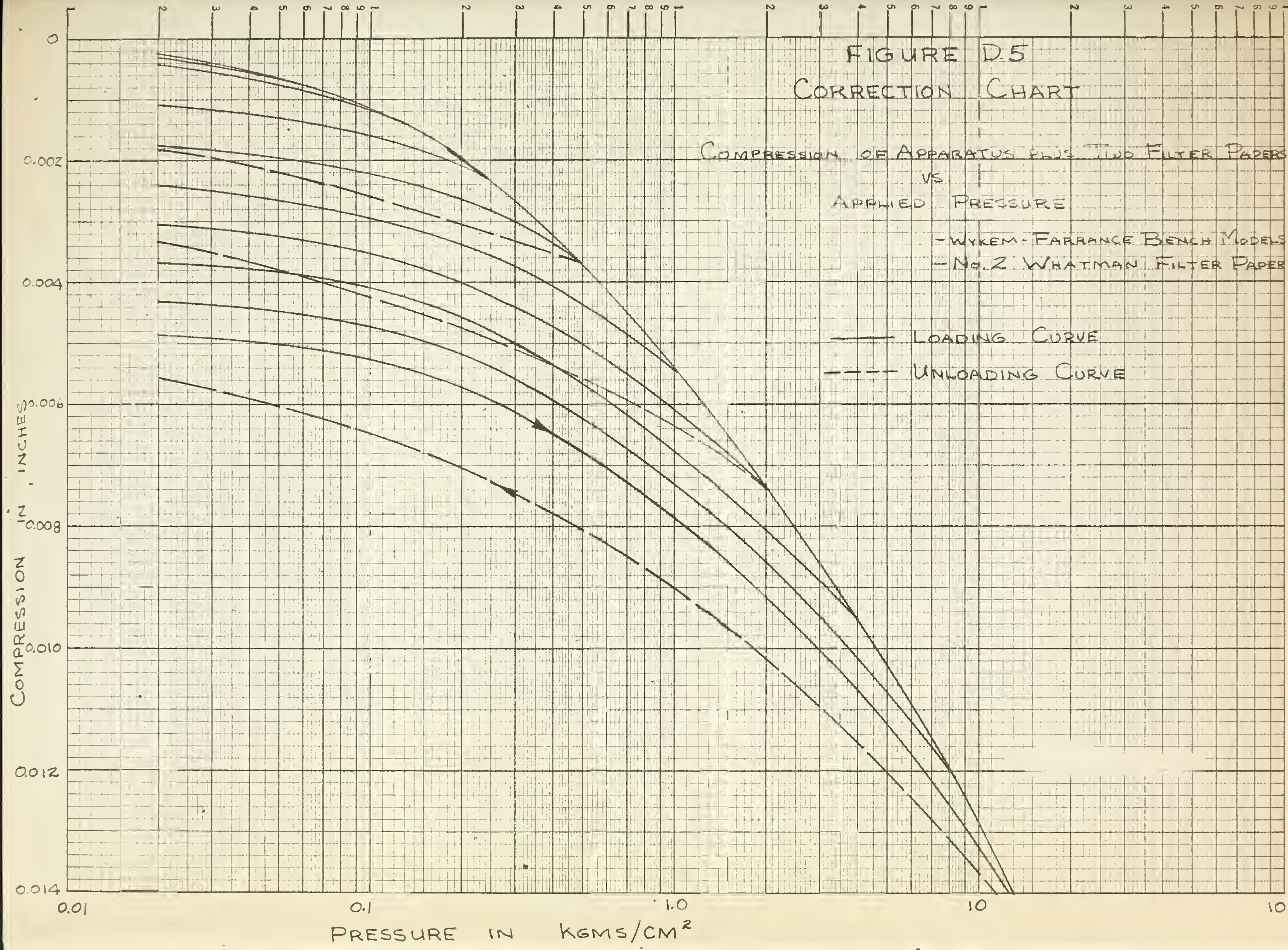


FIGURE D.5
CORRECTION CHART
COMPRESSION OF APPARATUS PLUS TWO FILTER PAPERS
VS
APPLIED PRESSURE
- WYKEM-FARRANCE BENCH MODELS
- No. 2 WHATMAN FILTER PAPER
LOADING CURVE
UNLOADING CURVE
COMPRESSION IN INCHES
0
0.002
0.004
0.006
0.008
0.010
0.012
0.014
PRESSURE IN KGMS/CM²
0.01
0.1
1.0
10
100

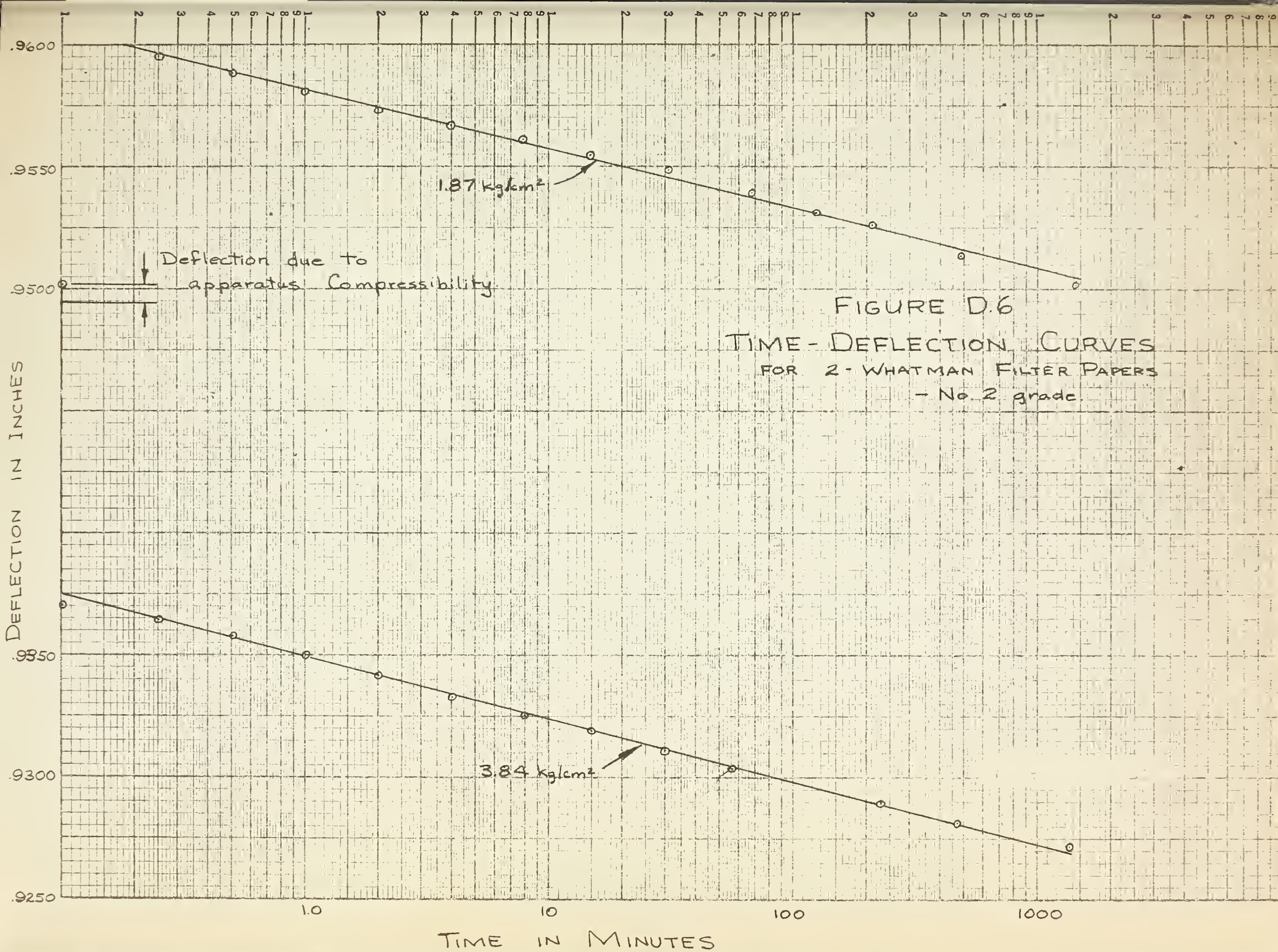


FIGURE D.6
TIME-DEFLECTION CURVES
FOR 2-WHATMAN FILTER PAPERS
- No. 2 grade

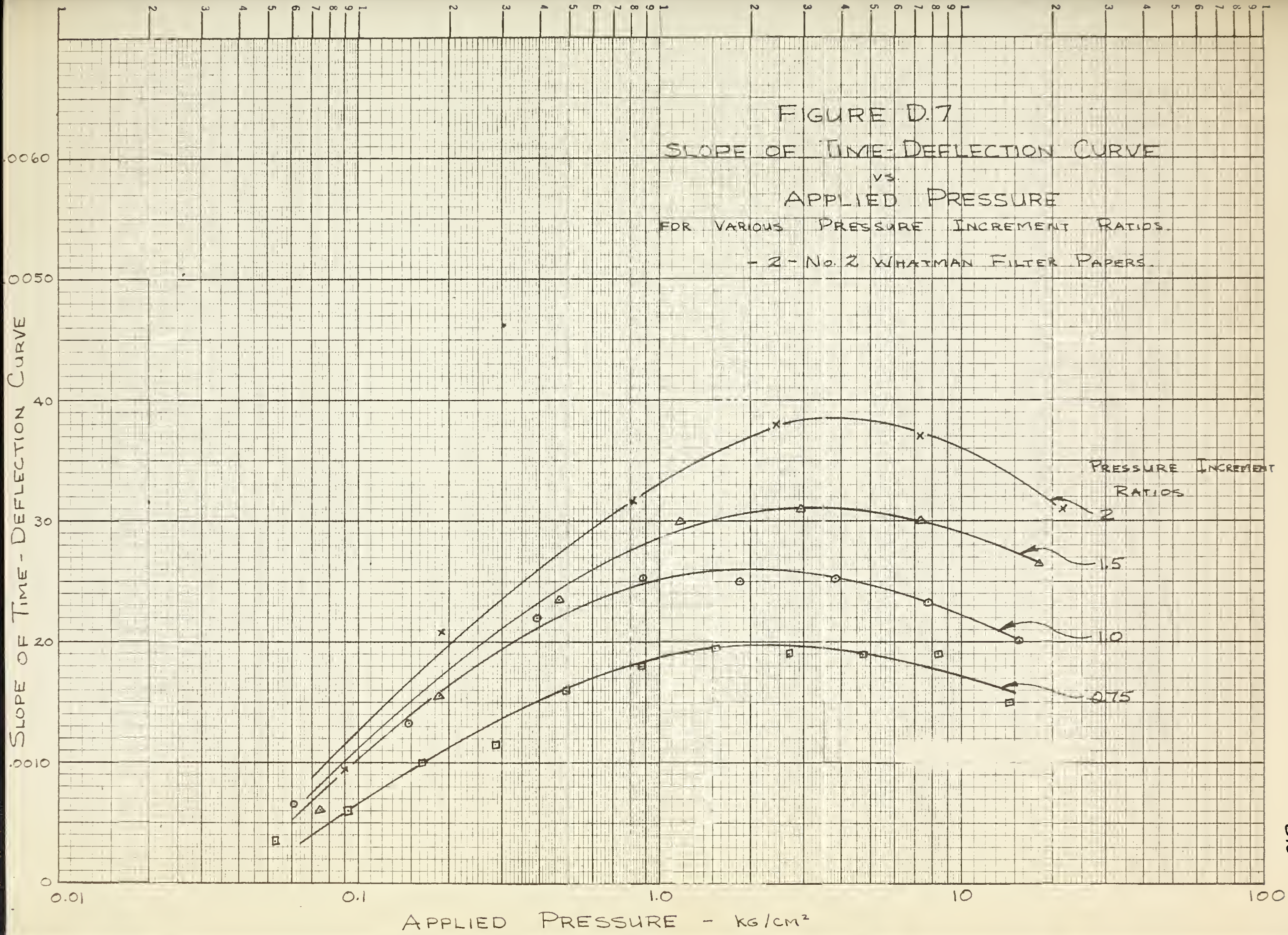


FIGURE D.7
SLOPE OF TIME-DEFLECTION CURVE
VS
APPLIED PRESSURE
FOR VARIOUS PRESSURE INCREMENT RATIOS.
- 2 - No. 2 WHATMAN FILTER PAPERS.
PRESSURE INCREMENT
RATIOS
2
1.5
1.0
0.75
SLOPE OF TIME - DEFLECTION CURVE
.0060
.0050
40
30
20
.0010
0
0.01
0.1
1.0
10
100
APPLIED PRESSURE - KG/CM²

Now the log time versus consolidation curves from a soil sample can be corrected for compression due to filter paper.

D:3 Side Friction in the Consolidation Ring

The friction of the soil against the side of the steel ring reduces the applied pressure which is effective in consolidating a soil. Leonards and Girault (1961) measured side friction during consolidation tests and plotted side friction as a per cent of the pressure increment versus the effective pressure. These values appear to be similar to those given in Lambe's Soil Testing for Engineers Laboratory Manual (1951). Corrections for side friction in this thesis were made on the assumption that the total frictional force was 16 per cent of the applied load.

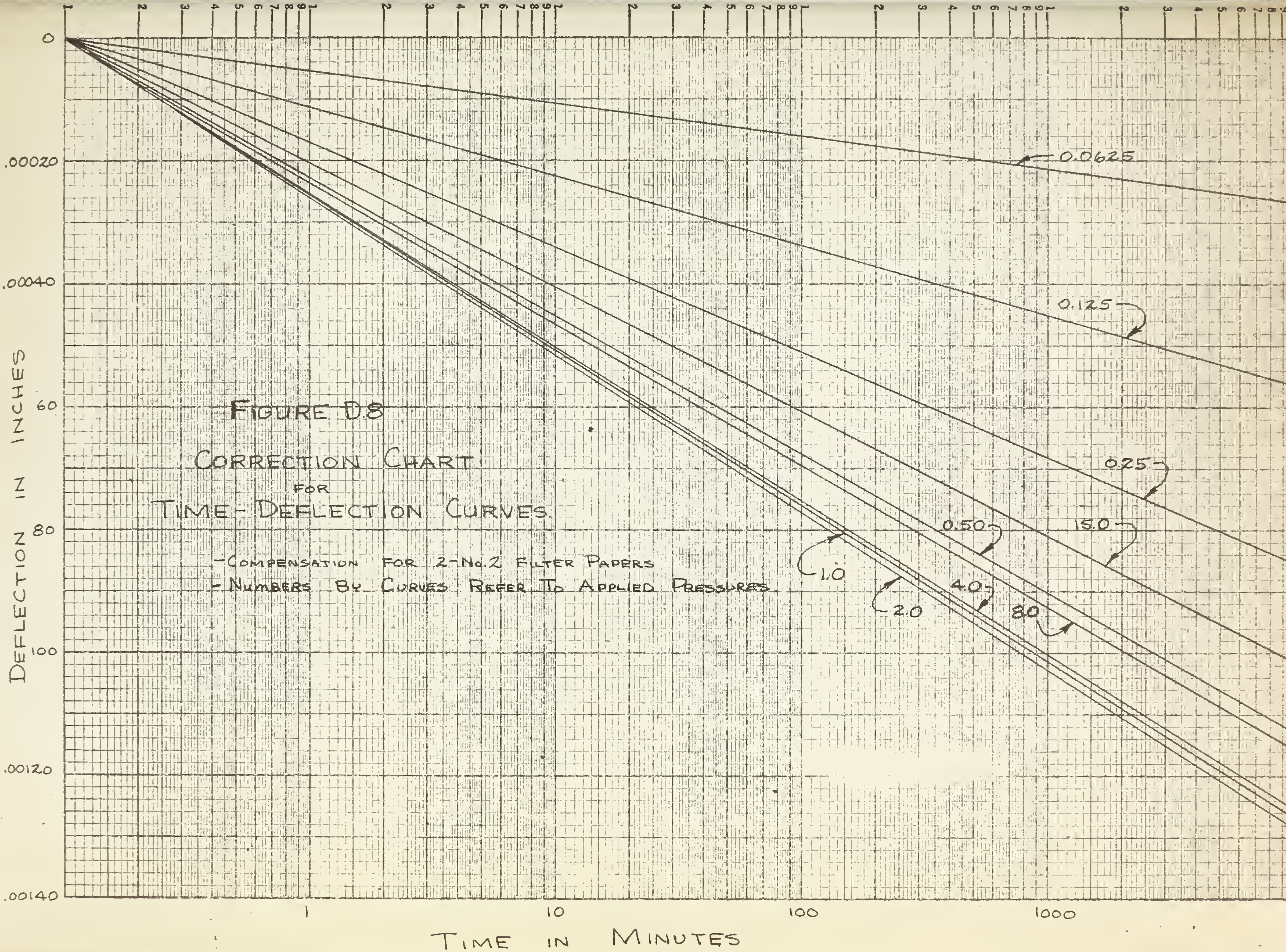


FIGURE D.8
CORRECTION CHART
FOR
TIME-DEFLECTION CURVES
-COMPENSATION FOR 2-No.2 FILTER PAPERS
-NUMBERS BY CURVES REFER TO APPLIED PRESSURES
0.0625
0.125
0.25
0.50
15.0
1.0
2.0
4.0
80
0
.00020
.00040
60
80
100
.00120
.00140
DEFLECTION IN INCHES
1
10
100
1000
TIME IN MINUTES

APPENDIX E

SUCTION TEST PROCEDURES

- Procedure for Sample Preparation

- Procedures for Pressure Plate and Pressure Membrane Extractors

- Procedure for Vacuum Desiccator

- Procedure for the New Pressure Plate Apparatus

APPENDIX E

SUCTION TEST PROCEDURES

E:1 Procedure for Sample Preparation

The method of sample preparation for the pressure plate and the pressure membrane extractors, as well as discussions on them, are outlined in considerable detail since suction tests are not a conventional engineering test. The disturbed soil from the field, in its natural water content condition was broken by hand until the maximum size was approximately 1/2-inch. After three days of air-drying in the laboratory, the sample was ground to pass a number 40 sieve. The soil was then mixed by hand, put through a sample splitter several times, and packaged in plastic bags. The aim of the above procedure was to obtain a soil as consistent as possible for the research program.

To destroy the original structure in the soil and obtain a new structure as uniform as possible, it was felt that a remolding water content similar to that of the flocculated sedimented sample should be used. When 50 grams of soil were added to 1000 cubic centimeters of water and mixed, the sample flocculated within five minutes and settled to a water content of 248 per cent after twenty-seven hours ($e \approx 7.0$). When varying amounts of sodium hexametaphosphate (Calgon) were added, flocculation occurred more slowly and retained a much higher water content. Since a water content of 248 per cent was too difficult to work with, from the consolidation standpoint, an arbitrary value of 100 per cent (well above

the liquid limit) was chosen for mixing samples prior to consolidation.

Specimens were prepared for the suction test in special lucite cylinders, 2 1/2 inches in diameter and 2 inches high, by consolidating the soil-water slurry from a water content of 100 per cent to any desired pressure. A porous stone and a filter paper was placed on each side of the sample. Consolidating machines at the University of Saskatchewan Soils Laboratory (PFRA design) were used for consolidating and rebounding samples. Due to friction in the apparatus, it was doubted whether much accuracy could be expected at pressure below 1/4 kg/cm^2. Therefore, samples at lower preconsolidation pressures were consolidated with a direct load mechanism. There appeared to be no problem encountered with stones binding against the lucite containers. A circular, teflon-coated steel ring was placed on the top porous stone to keep the applied load vertical. At the start of consolidation, the loads were applied in small increments in order to prevent soil from squeezing past the porous stones. After samples were consolidated to the desired pressure, they were rebounded under the weight of the porous stone (0.003 kg/cm^2) for about 48 hours.

The detailed procedure of sample preparation for both the pressure plate and pressure membrane extractors, can be outlined as follows:

1) The desired amount of soil to form several specimens was placed in a dish to which was added sufficient water to bring the water content to 100 per cent. Soaking was allowed for twenty-four to forty-eight hours and then the soil was thoroughly mixed.

2) Filter paper and porous stones were soaked in distilled water (No. 2,7 cm. diameter, Whatman filter paper). Filter paper was placed over the porous stone which was pushed into the bottom of the

lucite cylinder. Since the filter paper was larger than the porous stone, it folded over the edge to make a snug fit at the bottom.

3) Slurried soil was placed into the lucite cylinder with a spatula and tapped on the table top to remove entrapped quantities of air.

4) The lucite cylinder was filled to within 1/4-inch of the top.

5) Filter paper to be placed beneath the top porous stone was cut to the same diameter as the stone in order to decrease friction between the stone and the lucite container. The filter paper was placed on the porous stone which was in turn placed on the slurried soil.

6) The lucite container, specimen and porous stones were placed in the consolidation pot. Water was added to fill the consolidation pot.

7) Consolidation under the weight of the porous stone was allowed for about one hour. Then a steel ring was placed on the porous stone to which could be applied a vertical load by the consolidation apparatus. Usually the load was increased in increments with each increment allowed about two hours of consolidation.

8) After the desired consolidation pressure was on the specimen for at least twenty-four hours, it was rebounded to weight of the porous stone. The sample was allowed to take on water during the rebound time of at least forty-eight hours.

9) Samples were removed from the lucite cylinders by pushing the bottom porous stone upward. When the sample was about 1/8 inch out of the cylinder, a small sample was cut off with a wire saw for a water content determination.

10) After the specimen was removed from the lucite cylinder and trimmed, its volume was measured with calipers and its wet weight measured on a Mettler scale.

11) The specimen was then ready to be placed in either of the pressure plate or pressure membrane extractors.

E:2 Procedures for Pressure Plate and Pressure Membrane Extractors

The procedure used for the pressure plate extractor is somewhat revised from the usual procedure used by agricultural workers. It should be noted that proper care in handling soil samples is a necessity for accurate, consistent results. Samples were placed on the porous plate in a small excess of water. The chamber was closed and the desired positive pressure applied. A buret indicates when the outflow of water from the samples has ceased. Before releasing the pressure in the chamber, a pinch clamp was placed on the outflow tube which prevents the backflow of water to the samples after the chamber pressure is released. To avoid changes in the moisture content of the samples, they were quickly transferred to tare tins. The wet weight and the volume were measured at each equilibrium pressure.

Special precautions to be observed when using this apparatus are as follows:

1) Care must be taken to keep soil away from the cover gasket and seal.

2) The cover should never be removed with pressure in the chamber and care should be taken to see that the cover is properly in place before pressure is admitted to the chamber.

3) Pressures in the chamber should not exceed 1.4 kg/cm^2.

A detailed outline of the procedure used for the pressure plate extractor is as follows:

1) Initially, an effort was made to saturate the ceramic plates by placing water on them and applying a pressure of about 1 kg/cm^2 to force the water through. This procedure was repeated for several hours.

2) Approximately 1/16-inch of water was poured on the porous plate to ensure good contact between the soil and the porous plate.

3) As the specimens were prepared (Step 9 in Procedure for Preparation of Samples), they were placed on the ceramic plate and rotated horizontally with a slight vertical pressure.

4) After all specimens were in the extractor, the cover was fastened and the desired pressure applied.

5) At least twenty-four hours was allowed for specimens to come to equilibrium. Equilibrium was assured by attaching a buret to the drain and noting when no further volume change occurred.

6) The drains were clamped so no water could move from the ceramic plate into the specimen.

7) The chamber pressure was reduced to zero and the lid removed.

8) Samples were placed in tare tins as quickly as possible to prevent evaporation. Any small pieces of soil which remained on the ceramic plate were removed with a spatula and placed in the tare tin. The wet weight was measured to the nearest thousandth of a gram. The volume of the sample was measured by mercury immersion. Record was also kept of the diameter measurement by means of a caliper.

9) Water was again poured onto the ceramic plate.

10) All samples were returned to the extractor and the next pressure increment applied.

11) The above procedure was repeated until the last increment, after which the samples were either dried immediately in the oven at 103°C or else dried slowly in a moist atmosphere with volume and water content measurements being taken after different length of drying.

12) All samples were removed from the oven, placed in a desiccator and cooled to room temperature prior to measuring their dry weight.

13) Record was kept of the dry weight of small pieces of soil which remained in the tare tins after each pressure increment and were used to correct the calculations for specific bulk volume and water content.

The procedure for the pressure membrane extractor is similar in most respects to that just described. However, several parts of the procedure which were different are reviewed in a general way.

A cellulose membrane must be mounted over a screen plate in the extractor. The disc of cellulose casing was thoroughly soaked in water for approximately twenty-four hours and centered on the screen-drain plate. Care must be exercised in handling the cellulose membrane when it is in the stiff, dry condition, to avoid sharp creases which will cause tiny cracks.

The procedure for handling the samples is similar to that for the pressure plate extractor. The time for equilibrium was approximately 48 hours due to the impermeable nature of the membrane.

Regulation of the applied pressure was more complicated in the

pressure membrane extractor and can be outlined as follows:

1) Before the chamber pressure was turned on, the clamping bolts were tightened down. A torque of only 4 or 5 foot pounds is required to adequately seal the unit.

2) The bypass valve was initially left open to prevent disturbance to the samples and damage to the compression diaphragm.

3) The pressure regulator was now opened and adjusted to the pressure desired.

4) After the level of water in the buret becomes fairly constant, the samples have attained substantial rigidity and the compression diaphragm could be applied without disturbance to the samples.

5) To apply the compression diaphragm, the bypass valve was closed, then the exhaust valve was opened and air exhausted until air could be heard bubbling past the mercury in the U-tube.

6) The exhaust valve was then closed. The mercury U-tube had sufficient mercury in it to develop a differential pressure of 0.14 kg/cm^2. Therefore, the pressure behind the diaphragm was now 0.14 kg/cm^2 more than the pressure in the soil chamber.

The diaphragm action holds the samples firmly in contact with the cellulose membrane and considerably hastens equilibrium of the samples. For silts and medium-textured soils the diaphragm is unnecessary.

Both the pressure plate and pressure membrane extractors appeared to operate quite satisfactorily. However, a few of the problems encountered are worth mentioning. Due to the types of apparatus used, the best procedure to determine the equilibrium conditions of the sample was to remove the total sample and determine its wet weight and volume. Therefore,

it was necessary to reduce the chamber pressure to atmospheric pressure after each pressure increment. Calculations based on the measurement of the total volume of the sample showed only a slight decrease in the degree of saturation and this may be due in part to the rebound which occurs each time the pressure chamber is reduced to atmospheric conditions. However, the equilibrium water content and specific bulk volume calculations should not have an error of any significance.

When the soil samples were lifted from the apparatus after each pressure increment, small amounts of soil often remained on the ceramic plate or the cellulose membrane. The amount of soil was usually in the order of 0.001 to 0.010 gms. dry weight, but in a couple of cases was as high as 0.100 gms. A summation of the dry soil lost up to each pressure increment was added to the final dry soil weight to give the proper dry weight for each water content determination. The volume of soil solids was also corrected for lost soil. However, the correction was different since, for a particular increment, the soil lost during that increment was not included in the volume measurement and, therefore, the dry weight of soil for the next higher pressure (lower dry weight of soil), was used.

Cracking of several samples occurred before the test was completed. It was felt to be due to friction between the ceramic plate and the specimen. However, the results from these samples appeared to be consistent with other samples.

A record was kept of the time required for the measurement of wet weight and total volume of the samples. Samples were removed from the extractor and placed in tare tins with an average time of 50 seconds per specimen. The average time to weigh each sample was also 50 seconds.

In order to measure the diameter with calipers and the volume by mercury immersion, an average of 4.8 minutes was required. The complete operation for five specimens required approximately 30 minutes.

The first results showed the degree of saturation to vary considerably without following any definite trend. Since such a discrepancy was most likely to arise from the volume measurement, an attempt was made to improve the method of measurement. Immersion in mercury was used for the measurement of total volume. After a wet specimen was immersed in mercury, a film of water formed a scum on the mercury which did not allow a tight fit of mercury against the lucite plate. However, by moving the edge of a lucite bar across the top of the glass container prior to each volume measurement, the scum was removed and more consistent measurements resulted.

The reproducibility of the volume results was checked by making repeated measurements on a steel plug that had a volume of 34.062 cubic centimeters. Six measurements by mercury immersion gave an average volume of 34.09 cubic centimeters. The average deviation from this mean was 0.07 cubic centimeters. This shows that, although volume measurements are recorded to the nearest hundredth of a cubic centimeter, they are only accurate to the nearest tenth.

E:3 Procedure for Vacuum Desiccator

The vacuum desiccator procedure was used to determine the water content corresponding to very high soil suctions. The procedure is as follows:

1) Pyrex sample containers with ground glass lids were cleaned, dried at 103^{o} Centigrade and weighed to the nearest ten thousandth of a

gram.

2) Approximately two grams of soil were placed in each sample container.

3) The samples were placed in desiccators in which the controlled aqueous vapor pressure was approximately at 10%, 50%, 90% and 95% relative humidity. Slurried salt solutions were used to maintain constant vapor pressures. The salts used and their respective relative humidities produced were:

Lithium chloride - 11.3%

Calcium nitrate - 53.0%

Potassium nitrate - 92.8%

Potassium sulphate - 97.0%

Each salt solution was prepared by adding water to the dry salt and stirring with a glass rod until a fairly loose slush was developed.

Continuous record was kept of the temperature in the desiccators and an average value used for the relative humidity determination. A typical plot of the relationship between temperature and humidity for a particular salt is shown on FIGURE E.1 The relative humidity of each salt was also checked against a calibrated relative humidity probe.

4) The samples were placed in the various desiccators which were then evacuated with a vacuum pump.

5) The desiccators were opened at the end of three weeks.

6) The ground glass lids were quickly placed on the samples. Their weight plus tare was measured to the nearest ten thousandth of a gram. (All handling of sample containers was with a wire holder).

7) Samples were returned to the desiccators for another week,

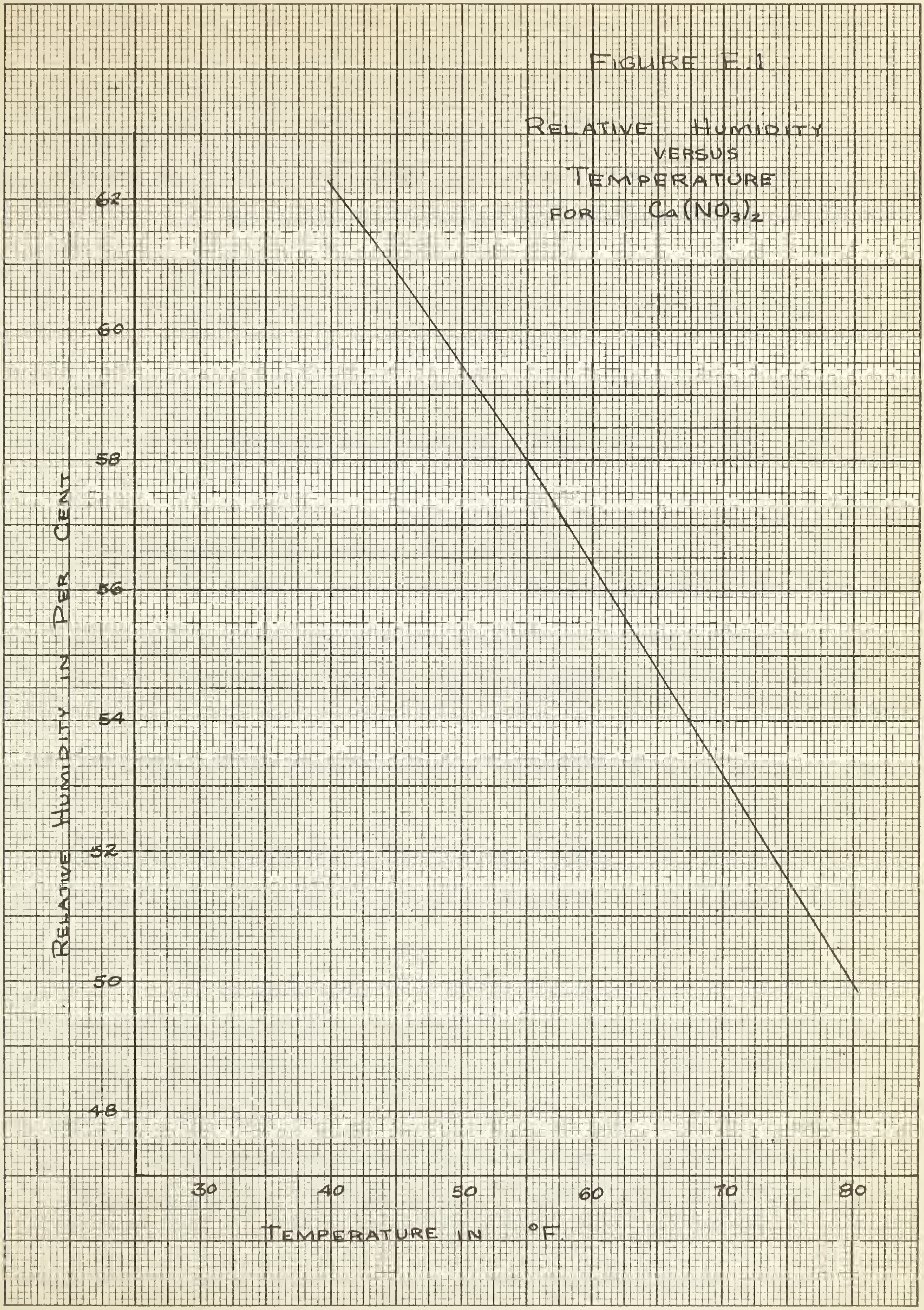


FIGURE E.1
RELATIVE HUMIDITY
VERSUS
TEMPERATURE
FOR $Ca(NO_3)_2$
62
60
58
56
54
52
50
48
30
40
50
60
70
80
RELATIVE HUMIDITY IN PER CENT
TEMPERATURE IN °F

and then weighed again. If the change in weight did not exceed one thousandth of a gram, equilibrium was assumed to have been reached.

8) The samples were dried at 103^{o} Centigrade and the moisture contents calculated.

9) Soil suction values were calculated from the formula

$$pF = 6.5 + \log (2 - \log \text{relative humidity}).$$

and pF was in turn converted to a pressure in kg/cm^2 (D.S.I.R., 1952).

The above procedure appeared to give favourable results and no problems were encountered during the tests.

E:4 Procedure for New Pressure Plate Apparatus

The new pressure plate apparatus was designed to perform suction tests on individual samples in the range of soil suctions from 0 to 1 kg/cm^2. Tests may be performed either on remolded samples in a slurried condition or on undisturbed soil samples. If remolded slurried samples are tested, vacuum grease or a similar grease should be placed on the glass above the porous stone in the pressure chamber in order to prevent the soil from adhering to the sides of the chamber. Undisturbed samples with a diameter of approximately 2 inches can be placed on the porous stone and tested by the following procedure.

1) Prior to the test, the porous stone must be saturated with deaired water by subjecting a pressure to the water placed above the porous stone. Also the top of the porous stone must not have free water on it at the time the sample is placed on it.

2) The valve below the pressure chamber is closed when the sample is placed on the porous stone. It remains closed until the top of

the pressure chamber is fastened and the desired pressure applied to the air in the pressure chamber.

3) After an initial reading is taken on the buret, the valve is opened and the timer is started at the same time. Readings in the buret are taken at time intervals varying on a logarithmic scale (eg. 0.1, 0.25, 0.5, 1,2,4,8,15-----minutes). When the buret becomes filled, the valve below the pressure chamber is closed and the plastic connection between the chamber and the buret is removed. This allows the buret to be drained with no volume change occurring in the sample. A new initial buret reading must then be registered before opening the valve below the pressure chamber.

4) Buret reading is plotted versus log time and after theoretical one hundred per cent consolidation has resulted, the chamber pressure is increased to the next increment. Applied pressures or soil suctions are applied on a logarithmic scale (eg. 0.031, 0.062, 0.125, 0.25, 0.5 and 1.0 kg/cm^2). However, if it is desired to measure the actual soil suction of a sample rather than the soil suction characteristics, the applied pressure in the chamber is increased or decreased while the volume reading in the buret is kept constant. The point where neither a volume decrease or increase results is the soil suction of the soil sample.

5) After both the increasing and decreasing soil suction characteristics are measured, the valve below the pressure chamber is closed, the top of the chamber removed and the soil sample quickly transferred to a water content tare.

6) From the measurement of the final water content, the correponding water content for other soil suctions can be calculated. It

should be noted that the test procedure and calculations are very similar to those of the conventional one-dimensional consolidation test.

APPENDIX F

<u>TESTING PROGRAM</u>

- Tests Performed

APPENDIX F

TESTING PROGRAM

F:1 Tests Performed

A summary of the test performed for the laboratory testing program are briefly summarized in this appendix.

Pressure Plate Extractor

Test No.	Preconsol'n Pressure kg/cm^2	Remarks
1 & 2	--	Slurried sample at 250 per cent water content. Placed in lucite ring in apparatus. Vol-W/C measurements to dry conditions on #1.
3A & 4A	1/32	According to outlined procedure. A repeat of 3 and 4 which had a mistake in procedure. Vol-W/C measurements on 3A until dry conditions.
5 & 6	1/16	Regular procedure. Vol-W/C measurements until dry on #6.
7 & 8	1/8	Regular procedure. Vol-W/C measurements until dry on #7.
9 & 10	1/4	Regular procedure. Vol-W/C measurements until dry on #9.
17 & 18	1/2	Regular procedure. Vol-W/C measurements until dry on #17.

.....Table continued

Pressure Plate Extractor (Cont'd)

Test No.	Preconsol'n Pressure kg/cm^2	Remarks
19 & 20	1	Regular procedure.
21 & 22	2	Regular procedure. Vol-W/C measurements until dry on #21.
23 & 24	4	Regular procedure. Vol-W/C measurements until dry on #24.

Pressure Membrane Extractor

Test No.	Preconsol'n Pressure kg/cm^2	Remarks
11 & 12	1/2	Regular procedure except samples disturbed. No volume measurements.
25 & 26	1/2	Regular procedure.
13 & 14	1	Regular procedure except sample disturbed and no volume measurement.
27 & 28	1	Regular procedure.
15 & 16	2	Regular procedure except samples disturbed and no volume measurement.
29 & 30	2	Regular procedure.
31 & 32	4	Regular procedure.

Volume-Water Content Measurement

Test No.	Remarks
U-12 U-13 U-14 U-1	Soil was remolded at 100 per cent water content and slowly dried while volume and water content measurements were taken. Approximate sample diameter was 4 centimeters.

Vacuum Desiccator Tests

Test No.	Relative Humidity (Per cent)	Remarks
56 31 22 98	11.3 52.9 92.7 97.0	Ground-up soil, oven-dried before the test.
3 11 59 46	11.3 52.9 92.7 97.0	Soil was remolded at a water content of 100 per cent. Then oven-dried prior to test in vacuum desiccator.
97 76 18 34	11.3 52.9 92.7 97.0	Ground up soil was remolded at a water content slightly in excess of the estimate equilibrium water content.

New Pressure Plate Apparatus Tests

Test No.	Remarks
40 & 41	Remolded at 100 per cent water content and poured into the pressure chamber. Therefore, zero pre-consolidation.

One-Dimensional Consolidation Tests

Test No.	Preconsol'n Pressure kg/cm^2	Remarks
55	0.0638	Consolidated from a slurried condition according to the regular outlined procedure.
54	0.247	Regular procedure.
51	0.486	Regular procedure.
52	2.026	Regular procedure.
50	4.06	Regular procedure.

APPENDIX G

TEST RESULTS

- Summary of Suction Tests
- Summary of Shrinkage Tests
- Summary of One-Dimensional Consolidation Tests
- Example Data Sheets

APPENDIX G

TEST RESULTS

G:1 Introduction

This appendix contains a complete summary of all test results obtained from the testing program. Only a graphical representation of results is given in Chapter VI because of the large number of test results. Example data sheets from each type of suction test are also shown.

TABLE NO.	TESTS RESULTS SUMMARIZED
G.1	Suction tests performed on the pressure plate extractor.
G.2	Suction tests performed on the pressure membrane extractor.
G.3	Water content, specific bulk volume and degree of saturation for samples dried by evaporation.
G.4	Suction tests performed in the vacuum desiccator.
G.5	Consolidation results from the new pressure plate apparatus.
G.6	Consolidation results from the one-dimensional consolidation tests.

Example data sheets are shown for the following tests:

- Suction test with the Pressure Plate Extractor.
- Suction test with the Pressure Membrame Extractor.
- Shrinkage Tests.
- Suction test with the New Pressure Plate Apparatus.

TABLE G.1

SUMMARY OF SUCTION TEST DATA
PRESSURE PLATE EXTRACTOR

NOTE - All samples (with the exception of #1 and #2) were initially remolded at a water content of approximately 100 per cent consolidated in lucite rings to various pressures and rebounded prior to being placed in the Pressure Plate Extractor.

.... Table Continued

TABLE G.1 (Continued)

SUMMARY OF SUCTION TEST DATA PRESSURE PLATE EXTRACTOR

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
1	0 - Initially Slurried	269.7	1/32	106.41	----	----
			1/16	87.39	1.233	98.7
			1/8	76.55	1.172	93.3
			1/4	68.07	1.093	91.8
			1/2	60.10	0.995	95.0
			1	50.95	0.902	92.8
2	0 - Initially Slurried	269.7	1/32	107.50	----	----
			1/16	89.02	----	----
			1/8	77.66	----	----
			1/4	68.53	----	----
			1/2	59.29	----	----
			1	50.57	----	----
3A	1/32	95.25	1/32	86.33	----	----
			1/16	80.54	1.189	95.8
			1/8	73.27	1.147	92.2
			1/4	64.10	1.038	93.5
			1/2	57.05	0.972	92.1
			1	49.04	0.889	91.4
4A	1/32	90.95	1/32	85.77	----	----
			1/16	80.10	1.191	95.4
			1/8	73.01	1.156	90.8
			1/4	63.58	1.043	92.1
			1/2	56.75	0.978	90.7
			1	48.85	0.902	88.9
5	1/16	85.83	1/32	80.25	----	----
			1/16	76.13	1.154	94.6
			1/8	71.75	1.111	94.6
			1/4	65.55	1.055	93.4
			1/2	58.61	0.967	95.4
			1	49.77	0.873	95.8
6	1/16	87.78	1/32	83.37	----	----
			1/16	78.55	1.170	95.8
			1/8	73.44	1.124	95.1
			1/4	66.94	1.058	94.9

.... Table Continued

TABLE G.1 (Continued)

SUMMARY OF SUCTION TEST DATA PRESSURE PLATE EXTRACTOR

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
			1/2	59.85	0.996	92.9
			1	50.60	0.887	94.7
7	1/8	80.33	1/32	79.01	----	----
			1/16	76.53	1.146	96.3
			1/8	72.65	1.110	95.9
			1/4	66.59	1.049	95.6
			1/2	59.73	0.989	93.8
			1	50.36	0.880	95.5
8	1/8	81.21	1/32	79.76	----	----
			1/16	77.23	1.154	95.8
			1/8	72.86	1.115	95.6
			1/4	66.92	1.072	93.1
			1/2	59.80	0.995	93.2
			1	50.69	0.896	93.3
9	1/4	73.23	1/32	73.38	----	----
			1/16	72.27	1.100	96.6
			1/8	70.16	1.079	96.5
			1/4	65.85	1.035	96.5
			1/2	59.25	0.975	95.3
			1	50.42	0.879	95.7
10	1/4	73.36	1/32	73.41	----	----
			1/16	72.36	1.096	97.1
			1/8	70.23	1.085	95.8
			1/4	65.79	1.046	94.9
			1/2	59.24	0.985	93.6
			1	50.39	0.922	91.3
17	1/2	61.18	1/32	62.00	1.018	93.1
			1/16	61.47	1.013	93.1
			1/8	60.51	1.005	92.8
			1/4	58.23	0.982	92.5
			1/2	54.94	0.953	91.5
			1	48.10	0.883	90.6
18	1/2	61.21	1/32	62.15	1.025	92.4
			1/16	61.87	1.018	93.0
			1/8	60.85	1.013	92.2

.... Table Continued

TABLE G.1 (Continued)

SUMMARY OF SUCTION TEST DATA PRESSURE PLATE EXTRACTOR

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
			1/4	58.52	0.991	91.6
			1/2	54.87	0.960	90.3
			1	48.17	0.890	89.7
21	2	49.31	1/32	52.70	0.903	95.7
			1/16	52.55	0.902	95.6
			1/8	51.72	0.891	96.1
			1/4	50.30	0.882	94.9
			1/2	48.60	0.864	94.9
			1	54.23	0.836	93.6
22	2	49.41	1/32	52.95	0.907	95.5
			1/16	52.75	0.906	95.4
			1/8	51.85	0.900	94.7
			1/4	50.32	0.883	95.0
			1/2	48.52	0.868	94.2
			1	45.15	0.837	93.2
23	4	44.60	1/32	51.54	0.889	96.0
			1/16	51.16	0.889	95.5
			1/8	50.09	0.878	95.4
			1/4	48.40	0.869	93.8
			1/2	46.42	----	----
			1	43.04	0.815	93.2
24	4	44.14	1/32	50.20	0.869	97.1
			1/16	50.03	0.869	96.9
			1/8	49.16	0.861	96.8
			1/4	47.64	0.847	96.4
			1/2	45.75	0.828	96.2
			1	42.43	0.798	95.4

TABLE G.2

SUMMARY OF SUCTION TEST DATA
PRESSURE MEMBRANE EXTRACTOR

NOTE - All samples were initially remolded at a water content of approximately 100 per cent, consolidated in lucite rings to various pressures and rebounded, prior to being placed in the Pressure Membrane Extractor.

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
11	1/2	62.42	1/2	57.73	0.988	91.0
			1.28	48.08	----	----
			2.39	41.70	----	----
			4.36	36.06	----	----
12	1/2	62.34	1/2	55.86	0.946	94.1
			1	48.50	0.872	93.5
			2	43.31	0.862	91.5
			3.30	37.77	0.753	94.4
			8.40	30.72	0.685	92.5
			12.20	28.74	0.664	92.2
25	1/2	60.51	1/2	55.86	0.946	94.1
			1	48.50	0.872	93.5
			2	43.31	0.826	91.5
			3.30	37.77	0.753	94.4
			8.40	30.72	0.685	92.5
			12.20	28.74	0.664	92.2
26	1/2	60.69	1/2	56.40	0.951	94.2
			1	48.69	0.874	93.4
			2	43.18	0.827	91.1
			3.30	38.13	0.756	94.5
			8.40	30.79	0.685	92.6
			12.20	28.80	0.668	91.3
13	1	50.86	1/2	49.43	0.884	93.1
			1.28	45.19	----	----
			2.39	41.02	----	----
			4.36	36.14	----	----
			8.26	31.09	----	----

.... Table Continued

TABLE G.2 (Continued)

SUMMARY OF SUCTION TEST DATA PRESSURE MEMBRANE EXTRACTOR

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
14	1	51.07	1/2	49.55	0.865	96.7
			1.28	45.63	----	----
			2.39	41.25	----	----
			4.36	36.75	----	----
			8.26	31.67	----	----
			12.30	28.61	----	----
27	1	54.38	1/2	51.63	0.897	94.7
			1	47.30	0.854	94.4
			2	42.19	0.809	92.5
			3.30	37.64	0.752	94.2
			8.40	30.83	0.685	92.8
			12.20	28.82	0.668	91.2
28	1	54.49	1/2	52.59	0.993	95.7
			1	48.18	0.857	95.7
			2	43.40	0.816	93.7
			3.30	38.08	0.753	95.3
			8.40	30.90	0.689	92.5
			12.20	28.89	0.666	92.1
15	2	49.85	1/2	49.09	0.878	93.4
			1.28	44.64	----	----
			2.39	40.82	----	----
			4.36	35.91	----	----
16	2	50.99	1/2	49.80	0.879	94.6
			1.28	45.10	----	----
			2.39	40.97	----	----
			4.36	36.86	----	----
			8.26	31.93	----	----
			12.30	28.48	----	----
29	2	49.48	1/2	47.64	0.847	96.3
			1	44.97	0.822	95.9
			2	41.72	0.793	94.8
			3.30	37.59	0.746	95.5
			8.40	30.81	0.682	93.6
			12.20	28.75	0.662	93.0

.... Table Continued

TABLE G.2 (Continued)

SUMMARY OF SUCTION TEST DATA PRESSURE MEMBRANE EXTRACTOR

SAMPLE NO.	PRECONSOL'N LOAD (kg/cm^2)	INITIAL WATER CONTENT (Per Cent)	APPLIED PRESSURE (kg/cm^2)	EQUILIBRIUM WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)
30	2	49.30	1/2	48.27	0.854	96.2
			1	45.20	0.823	96.1
			2	41.86	0.791	95.5
			3.30	37.81	0.751	95.0
			8.40	30.81	0.680	94.1
			12.20	28.97	0.663	93.4
31	4	45.07	1/2	45.20	0.820	96.8
			1	42.94	0.813	93.3
			2	40.13	----	----
32	4	44.39	1/2	44.82	0.817	96.4
			1	42.39	0.793	96.2
			2	39.95	0.767	96.5
			3.30	37.12	0.742	95.3
			8.40	30.79	----	----
			12.20	29.56	----	----

TABLE G.3

SUMMARY OF SHRINKAGE TESTS

SAMPLE NO.	WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)	REMARKS
1	39.45	0.767	95.2	Volume-water content measurements on sample taken from Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation load was 0 kg/cm^2.
	30.37	0.690	90.1	
	24.68	0.637	86.9	
	14.82	0.551	74.8	
	11.19	0.536	61.1	
	9.17	0.525	53.2	
	6.04	0.550	30.6	
	5.30	0.520	3.2	
	0	0.518	0	
3A	49.04	0.889	91.4	Suction test sample removed from the Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation load was 1/32 kg/cm^2.
	47.12	0.886	91.8	
	41.72	0.809	91.4	
	38.02	0.777	89.7	
	32.17	0.713	89.2	
	27.67	0.670	87.1	
	25.43	0.646	86.7	
	20.37	0.597	83.4	
	9.14	0.543	47.9	
	0	0.537	0	
6	41.97	0.796	94.6	Suction test sample removed from the Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation Pressure was 1/16 kg/cm^2.
	35.50	0.736	92.6	
	31.05	0.689	92.3	
	22.37	0.608	87.7	
	18.27	0.566	85.8	
	15.04	0.548	76.9	
	12.06	0.536	65.8	
	8.83	0.529	50.1	
	7.52	0.526	43.2	
	6.79	0.528	38.8	
	0	0.526	0	
7	42.31	0.796	95.3	Suction test sample removed from Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation Pressure was 1/8 kg/cm^2.
	37.05	0.747	93.9	
	33.39	0.712	92.8	
	26.36	0.641	91.3	
	21.99	0.597	90.2	
	18.40	0.571	84.4	
	14.21	0.542	75.1	
	9.62	0.523	56.4	

.... Table Continued

TABLE G.3 (Continued)

SUMMARY OF SHRINKAGE TESTS

SAMPLE NO.	WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)	REMARKS
	7.97	0.525	46.1	
	6.83	0.523	40.1	
	6.16	0.517	37.4	
	0	0.516	0	
9	42.02	0.799	94.3	Suction test sample removed from Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation Pressure was 1/4 kg/cm^2.
	36.67	0.750	92.4	
	33.02	0.711	92.2	
	24.99	0.631	89.7	
	20.83	0.583	90.4	
	17.29	0.564	81.8	
	13.36	0.538	72.2	
	9.33	0.529	52.9	
	7.88	0.533	43.7	
	6.95	0.525	40.4	
	6.20	0.516	37.9	
	0	0.512	0	
17	48.10	0.883	90.6	Suction test sample removed from Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation Pressure was 1/2 kg/cm^2.
	46.34	0.863	90.9	
	41.48	0.821	88.6	
	37.96	0.776	89.7	
	32.31	0.720	88.0	
	27.95	0.679	85.5	
	26.05	0.655	86.1	
	21.37	0.609	83.5	
	10.13	0.553	50.6	
	0	0.534	0	
21	45.23	0.836	93.6	Suction test sample removed from Pressure Plate Extractor after the 1 kg/cm^2. Initial Preconsolidation Pressure was 2 kg/cm^2.
	43.74	0.823	93.0	
	39.54	0.782	92.2	
	36.16	0.747	91.7	
	31.42	0.700	90.5	
	27.67	0.664	88.9	
	25.94	0.645	88.8	
	21.63	0.606	85.5	
	10.79	0.545	56.2	
	0	0.533	0	

.... Table Continued

TABLE G.3 (Continued)

SUMMARY OF SHRINKAGE TESTS

SAMPLE NO.	WATER CONTENT (Per Cent)	SPECIFIC BULK VOLUME (cc per gm)	DEGREE OF SATURATION (Per Cent)	REMARKS
24	42.43	0.806	95.4	Suction test sample removed from Pressure Plate Extractor after the 1 kg/cm^2 pressure. Initial Preconsolidation Pressure was 4 kg/cm^2.
	41.00	0.788	96.2	
	37.05	0.752	94.7	
	29.31	0.671	94.1	
	25.43	0.645	89.2	
	23.82	0.621	91.1	
	19.59	0.582	87.8	
	9.93	0.533	57.0	
	0	0.520	0	
U-12	101.47	1.391	97.8	Remolded at approximately 100 per cent water content and slowly dried. Original sample diameter = 3.95 cm.
	39.66	0.761	97.1	
	24.84	0.615	94.8	
	7.51	0.512	47.2	
	5.60	0.513	34.9	
	0	0.504		
U-13	109.97	1.482	97.4	Remolded at approximately 100 per cent water content and slowly dried.
	48.43	0.847	98.0	
	32.62	0.695	95.3	
	8.14	0.517	49.7	
	5.88	0.516	36.1	
	0	0.508	0	
U-14	109.86	1.468	98.5	Remolded at approximately 100 per cent water content and slowly dried.
	48.85	0.865	95.2	
	33.80	0.703	96.2	
	8.47	0.517	51.4	
	5.91	0.513	36.8	
	0	0.506	0	
U-1	97.49	1.352	97.6	Remolded at approximately 100 per cent water content and slowly dried.
	40.90	0.775	97.0	
	29.43	0.664	94.8	
	8.28	0.520	49.6	
	5.48	0.515	33.6	
	0	0.507	0	

TABLE G.4

SUMMARY OF VACUUM DESICCATOR

NOTE - Samples were prepared with various initial drying histories.

SAMPLE NO.	RELATIVE HUMIDITY % & SUCTION PRESSURE in kg/cm^2	EQUILIBRIUM WATER CONTENT (Per Cent)	REMARKS
56	11.3 (3,000)	1.9	Ground-up, oven-dried.
31	52.9 (800)	5.6	
22	92.7 (100)	12.9	
98	97.0 (40)	17.8	
3	11.3 (3,000)	2.2	Ground-up, oven-dried from 100 per cent water content.
11	52.9 (800)	6.1	
59	92.7 (100)	13.1	
46	97.0 (40	----	
97	11.3 (3,000)	3.7	Remolded soil wetted to just above the estimated equilibrium water content.
76	52.7 (800)	7.4	
18	92.7 (100)	15.9	
34	97.0 (40)	19.1	

TABLE G.5

SUMMARY OF CONSOLIDATION RESULTS

FROM THE SUCTION TESTS

				Log. Time			Square Root Time		
Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inc't Ratio	Ht. of Sample (cm.)	t_{50} (Min.)	H_{50} (cm.)	$C_v \times 10^{-4}$ (cm^2/sec)	t_{90} (Min.)	H_{90} (cm.)	$C_v \times 10^{-4}$ (cm^2/sec)
Sample #40									
0.0313	90.80	--	1.300	56.5	1.40	1.14	234	1.32	1.05
0.062	83.22	1.00	1.222	90.0	1.261	0.581	324	1.230	0.663
0.125	73.55	1.00	1.127	58.5	1.175	0.775	196	1.137	0.933
0.25	66.17	1.00	1.050	77.0	1.089	0.506	279	1.058	0.567
0.50	58.18	1.00	0.969	117	1.010	0.286	429	0.977	0.314
0.75	54.68	0.50	0.933	213	0.951	0.140	770	0.937	0.161
1.00	50.83	0.33	0.895	--	0.914	--	1178	0.899	0.097
Sample #41									
0.0313	86.41	--	1.739	36.5	1.862	3.12	188	1.764	2.34
0.062	76.69	1.00	1.603	52.5	1.671	1.75	186	1.617	1.99
0.125	69.34	1.00	1.500	64.5	1.552	1.23	231	1.510	1.40
0.25	60.78	1.00	1.381	76.5	1.440	0.890	262	1.393	1.05
0.50	53.75	1.00	1.282	122	1.332	0.477	396	1.292	0.596
1.00	46.87	1.00	1.185	167	1.234	0.300	635	1.195	0.318

TABLE G.6

SUMMARY OF CONSOLIDATION RESULTS

FROM THE ONE-DIMENSIONAL CONSOLIDATION TESTS

Sample #50

Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inc't Ratio	Ht. of Sample (Inches)	t_{50} (Min.)	Log Time: H_{50} (Inches)	Log Time: $C_v \times 10^{-4}$ (cm^2/sec)	Square Root Time: t_{90} (Min.)	Square Root Time: H_{90} (Inches)	Square Root Time: $C_v \times 10^{-4}$ (cm^2/sec)
Consolidating									
0.0117	100.54								
0.0538	89.22	3.60	0.5303	23	0.2773	0.708	108	0.2676	0.663
0.148	76.84	1.75	0.4771	14.3	0.2518	0.937	48	0.2412	1.213
0.253	71.21	0.709	0.4529	29	0.2325	0.395	72	0.2276	0.656
0.500	60.88	0.976	0.4085	11.3	0.2153	0.867	46	0.2065	0.845
0.995	52.10	0.990	0.3707	10.0	0.1948	0.803	42	0.1872	0.760
1.98	44.20	1.00	0.3368	10.6	0.1769	0.625	41.5	0.1701	0.637
4.06	36.78	1.05	0.3049	9.4	0.1604	0.580	38	0.1540	0.569
Rebounding									
1.98	37.78								
0.500	40.74								
0.148	43.11								
0.0117	45.72								
Consolidating									
0.148	44.99								
0.393	43.78								
0.883	41.79								
1.87	39.41								
3.84	36.59								
7.78	31.07	1.03	0.2803	10.7	0.1461	0.422	19.8	0.1413	0.920
11.72	27.76								
19.78	23.71								
Rebounding									
11.72	24.66								
3.84	27.52								
0.885	31.77								
0.148	36.00								
0.0258	38.12								

SUMMARY OF CONSOLIDATION RESULTS

FROM THE ONE-DIMENSIONAL CONSOLIDATION TESTS

Sample #51

Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inc't Ratio	Ht. of Sample (Inches)	Log Time: t_{50} (Min.)	Log Time: H_{50} (Inches)	Log Time: $C_v \times 10^{-4}$ (cm^2/sec)
Consolidating						
0.0116	101.28					
0.0524	88.89	3.52	0.5002	19.0	0.2626	0.767
0.144	76.52	1.75	0.4502	13.2	0.2376	0.906
0.245	70.77	0.701	0.4269	41.0	0.2193	0.248
0.486	60.61	0.984	0.3858	11.1	0.2032	0.788
Rebounding						
0.144	62.27					
0.0116	65.23					
Consolidating						
0.144	63.47					
0.245	62.64					
0.381	61.48					
0.858	54.02					
1.814	44.38					
3.72	36.71					
7.55	30.29	1.03	0.2631	9.65	0.1381	0.418
Rebounding						
1.814	33.33					
0.381	37.40					
0.0116	42.69					

SUMMARY OF CONSOLIDATION RESULTS

FROM THE ONE-DIMENSIONAL CONSOLIDATION TESTS

Sample #52

Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inct Ratio	Ht. of Sample (Inches)	Log Time: t_{50} (Min.)	Log Time: H_{50} (Inches)	Log Time: $C_v \times 10^{-4}$ (cm^2/sec)
Consolidating						
0.0117	98.80					
0.0534	88.23	5.56	0.5723	25.2	0.2985	0.713
0.147	76.08	1.75	0.5157	16.4	0.2720	0.955
0.250	70.21	0.701	0.4884	25.4	0.2510	0.525
0.496	60.33	0.984	0.4424	13.8	0.2327	0.831
0.985	51.67	0.986	0.4020	12.9	0.2111	0.731
2.026	43.63					
Rebounding						
0.496	46.18					
0.147	47.95					
0.0117	50.32					
Consolidating						
0.0776	49.95					
0.319	48.60					
0.806	46.51					
1.78	43.88					
3.73	37.58					
7.64	30.79	1.05	0.3047	12.5	0.1603	0.415
Rebounding						
1.78	33.87					
0.319	38.25					
0.0117	41.52					

SUMMARY OF CONSOLIDATION RESULTS

FROM THE ONE-DIMENSIONAL CONSOLIDATION TESTS

Sample #54

Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inc't Ratio	Ht. of Sample (Inches)	Log Time: t_{50} (Min.)	Log Time: H_{50} (Inches)	Log Time: $C_v \times 10^{-4}$ (cm^2/sec)
Consolidating						
0.0422	89.94					
0.0762	85.10	0.806	0.5544	17.5	0.2827	0.965
0.247	70.10	2.24	0.4861	3.95	0.2601	0.362
Rebounding						
0.0422	71.78					
Consolidating						
0.144	70.91					
0.382	65.11					
0.859	53.70					
1.82	44.74					
3.73	37.88					
7.55	31.60	1.02	0.3105	10.7	0.1624	0.522
15.21	25.01					
Rebounding						
3.73	27.92					
0.859	31.63					
0.144	35.29					
0.0252	36.97					

SUMMARY OF CONSOLIDATION RESULTS

FROM THE ONE-DIMENSIONAL CONSOLIDATION TESTS

Sample #55

Pressure (kg/cm^2)	Equilibrium Water Content (Per Cent)	Load Inc't Ratio	Ht. of Sample (Inches)	Log Time t_{50} (Min.)	Log Time H_{50} (Inches)	$C_v \times 10^{-4}$ (cm^2/sec)
Consolidating						
0.0256	91.91					
0.0638	85.00					
Rebounding						
0.0256	85.42					
Consolidating						
0.0776	83.62					
0.147	76.52					
0.389	63.45	1.65	0.4657	4.5	0.2480	2.89
0.876	52.86	1.25	0.4167	6.55	0.2206	1.57
1.85	44.71					
3.81	37.35					
7.71	31.29	1.02	0.3167	11.6	0.1655	0.500
15.53	25.87					
Rebounded						
7.71	27.04					
0.876	32.61					
0.147	36.12					
0.0256	37.70					

[illegible]

Example Data Sheets

For Tests Performed With The

Pressure Plate Extractor

SUCTION TEST

SUMMARY AND COMPUTATION SHEET

PROJECT: THESIS DURATION OF TEST: AUG. 2/63 to AUG. 12/63

SAMPLE NO.: REGINA CLAY #9 NO. OF INCREMENTS: 6

SPECIFIC GRAVITY: 2.835 INITIAL WATER CONTENT: 73.23

REMARKS: SAMPLE WAS INITIALLY CONSOLIDATED TO 1/4 KG/CM^2 FROM A REMOLDING WATER CONTENT OF APPROXIMATELY 100 % PRIOR TO BEING PLACED IN THE PRESSURE PLATE APPARATUS.

Actual elapsed time for inc'm't.	Pressure (Kg/cm^2)	Water Content %	Void Ratio e	Per cent Saturation S	Dry Density γ_d	Specific Bulk Volume
[HOURS]						
28	1/32	73.38	—	—	—	—
43	1/16	72.27	2.120	96.6	56.7	1.100
34	1/8	70.16	2.061	96.5	57.8	1.079
38	1/4	65.85	1.935	96.5	60.3	1.035
37	1/2	59.25	1.763	95.3	64.0	0.975
59	1	50.42	1.493	95.7	70.9	0.879

PRESSURE PLATE EXTRACTOR

Specific Gravity of Soil Solids, G_s = 2.835 Project THESIS
Remarks = REMOLDED AT APPROXIMATELY 100% WATER CONTENT, PRECONSOLIDATED TO 1/4 KG/CM^2 AND REBOUNDED.
Sample REGINA CLAY #9
Location U. OF S. LAB.
Technician D. G. F.
Date AUG, 2/63

Initial Water Content		Initial Volume	
Wet Wt. + Tare	= 27.959	Diameter	6.35
Dry Wt. + Tare	= 20.988	Area Sq. cm.	31.67
Wt. Water	= 6.971	Thickness	2.00
Tare Container	= 11.449	Volume	63.3
Dry Soil	= 9.539		
Water Content %	= 73.08		

Initial Wet Wt. of Total Sample = 94.88 OR w/c = 73.23%

Date + Time AUG. 3/63 [15.00] Pressure 1/32 KG/CM^2

Water Content		Volume [NO VOLUME MEASUREMENT]	
Wet Wt. + Tare	= 132.085	Mercury + Tare	=
Tare # 9	= 37.121	Tare	=
Wet Wt. of Soil	= 94.964	Mercury	=
Correction for Lost Soil	= 0.108	Total Volume, V_t	=
Total Dry Wt. of Soil	= 54.771	Volume of Soil Solids, V_s	=
Wt. Water	= 40.193	Volume of Voids, V_v	=
Water Content %	= 73.38	Void Ratio, e	=
Dry Density γ_d	=	% Saturation, S	=

PRESSURE PLATE EXTRACTOR

Specific Gravity, G_s = 2.835 Sample = REGINA CLAY #9

Date + Time	AUG. 5/63 [10.00]	Pressure	1/16 KG/CM^2
Water Content		**Volume**	
Wet Wt. + Tare	= 131.416	Mercury + Tare	= 906.03
Tare # 9	= 37.121	Tare	= 91.60
Wet Wt. of Soil	= 94.295	Mercury	= 814.43
Correction for Lost Soil	= 0.075	Total Volume, V_t	= 60.19
Total dry Wt. of Soil	= 54.738	Volume of Soil Solids, V_s	= 19.29
Wt. Water	= 39.557	Volume of Voids, V_v	= 40.90
Water Content %	= 72.27	Void Ratio, e	= 2.120
Dry Density γ_d	= 56.7	% Saturation, S	= 96.6

Date + Time	AUG. 6/63 [20.00]	Pressure	1/8 KG/CM^2
Water Content		**Volume**	
Wet Wt. + Tare	= 130.178	Mercury + Tare	= 890.05
Tare # 9	= 37.124	Tare	= 91.60
Wet Wt. of Soil	= 93.054	Mercury	= 798.45
Correction for Lost Soil	= 0.024	Total Volume, V_t	= 59.01
Total Dry Wt. of Soil	= 54.687	Volume of Soil Solids, V_s	= 19.28
Wt. Water	= 38.367	Volume of Voids, V_v	= 39.73
Water Content %	= 70.16	Void Ratio, e	= 2.061
Dry Density γ_d	= 57.8	% Saturation, S	= 96.5

Date + Time	AUG. 8/63 [10.00]	Pressure	1/4 KG/CM^2
Water Content		**Volume**	
Wet Wt. + Tare	= 127.782	Mercury + Tare	= 857.07
Tare # 9	= 37.124	Tare	= 91.60
Wet Wt. of Soil	= 90.658	Mercury	= 765.47
Correction for Lost Soil	= —	Total Volume, V_t	= 56.58
Total Dry Wt. of Soil	= 54.663	Volume of Soil Solids, V_s	= 19.28
Wt. Water	= 35.995	Volume of Voids, V_v	= 37.30
Water Content %	= 65.85	Void Ratio, e	= 1.935
Dry Density γ_d	= 60.3	% Saturation, S	= 96.5

PRESSURE PLATE EXTRACTOR

Specific Gravity, G_s = 2.835 Sample = REGINA CLAY #9

Date + Time	AUG. 9/63 [23.00]	Pressure	1/2 KG/CM^2
Water Content		**Volume**	
Wet Wt. + Tare	= 124.176	Mercury + Tare	= 766.73
Tare # 9	= 37.124	Tare	= 45.80
Wet Wt. of Soil	= 87.052	Mercury	= 720.93
Correction for Lost Soil	= ——	Total Volume, V_t	= 53.28
Total dry Wt. of Soil	= 54.663	Volume of Soil Solids, V_s	= 19.28
Wt. Water	= 32.389	Volume of Voids, V_v	= 34.00
Water Content %	= 59.25	Void Ratio, e	= 1.763
Dry Density γ_d	= 64.0	% Saturation, S	= 95.3

Date + Time	AUG. 12/63 [10.00]	Pressure	1 KG/CM^2
Water Content		**Volume**	
Wet Wt. + Tare	= 119.348	Mercury + Tare	= 696.03
Tare # 9	= 37.124	Tare	= 45.80
Wet Wt. of Soil	= 82.224	Mercury	= 650.23
Correction for Lost Soil	= ——	Total Volume, V_t	= 48.06
Total Dry Wt. of Soil	= 54.663	Volume of Soil Solids, V_s	= 19.28
Wt. Water	= 27.561	Volume of Voids, V_v	= 28.78
Water Content %	= 50.42	Void Ratio, e	= 1.493
Dry Density γ_d	= 70.9	% Saturation, S	= 95.7

Date + Time		Pressure	
Water Content		**Volume**	
Wet Wt. + Tare	=	Mercury + Tare	=
Tare #	=	Tare	=
Wet Wt. of Soil	=	Mercury	=
Correction for Lost Soil	=	Total Volume, V_t	=
Total Dry Wt. of Soil	=	Volume of Soil Solids, V_s	=
Wt. Water	=	Volume of Voids, V_v	=
Water Content %	=	Void Ratio, e	=
Dry Density γ_d	=	% Saturation, S	=

Example Data Sheets

For Tests Performed With The

Pressure Membrane Extractor

SUCTION TEST

SUMMARY AND COMPUTATION SHEET

PRESSURE MEMBRANE APPARATUS

PROJECT: THESIS

DURATION OF TEST: AUG. 28/63 to ~~AUG.~~ SEPT. 12/63

SAMPLE NO.: REGINA CLAY #25

NO. OF INCREMENTS: 6

SPECIFIC GRAVITY: 2.835

INITIAL WATER CONTENT: 60.51

REMARKS: REMOLDED AT APPROXIMATELY 100% WATER CONTENT, CONSOLIDATED TO 1/2 KG/CM AND REBOUNDED PRIOR TO BEING PLACED IN THE PRESSURE MEMBRANE APPARATUS.

Actual elapsed time for inc'm't. [HOURS]	Pressure (Kg/cm^2)	Water Content %	Void Ratio e	Per cent Saturation S	Dry Density γ_d	Specific Bulk Volume
47	1/2	55.86	1.684	94.1	65.9	0.946
73	1	48.50	1.470	93.5	71.6	0.872
47 1/2	2	43.31	1.342	91.5	75.6	0.826
47	3.30	37.77	1.134	94.4	82.9	0.753
96 1/2	8.40	30.72	0.942	92.5	91.1	0.685
47 1/2	12.20	28.74	0.884	92.2	93.9	0.664

PRESSURE PLATE EXTRACTOR

Specific Gravity of Soil Solids, G_s = 2.835		Project	THESIS
Remarks = REMOLDED AT APPROXIMATELY 100 % WATER CONTENT, CONSOLIDATED TO 1/2 KG/CM^2 AND REBOUNDED PRIOR TO BEING PLACED IN PRESSURE MEMBRANE APPARATUS		Sample	REGINA CLAY #25
		Location	U. OF S. LAB.
		Technician	D. G. F.
		Date	AUG. 28/63 [11.00]

Initial Water Content		Initial Volume	
Wet Wt. + Tare	= 28.568	Diameter	6.35
Dry Wt. + Tare	= 22.040	Area Sq. cm.	31.67
Wt. Water	= 6.528	Thickness	1.60
Tare Container V-1	= 11.211	Volume	50.7
Dry Soil	= 10.829		
Water Content %	= 60.28		
Initial Wet Wt. of Total Sample	= 80.69 OR w/c = 60.51		

Date + Time AUG. 30/63 [10.00]		Pressure 1/2 KG/CM^2	
Water Content		**Volume**	
Wet Wt. + Tare	= 115.989	Mercury + Tare	= 689.57
Tare # 11	= 37.636	Tare	= 45.80
Wet Wt. of Soil	= 78.353	Mercury	= 643.77
Correction for Lost Soil	= 0.036	Total Volume, V_t	= 47.58
Total Dry Wt. of Soil	= 50.270	Volume of Soil Solids, V_s	= 17.73
Wt. Water	= 28.083	Volume of Voids, V_v	= 29.85
Water Content %	= 55.86	Void Ratio, e	= 1.684
Dry Density γ_d	= 65.9	% Saturation, S	= 94.1

PRESSURE PLATE EXTRACTOR

Specific Gravity, G_s = 2.835 Sample = REGINA CLAY #25

Date + Time	SEPT. 2/63 [11.00]	Pressure	1 KG/CM^2
Water Content		Volume	
Wet Wt. + Tare	= 112.266	Mercury + Tare	= 638.37
Tare # 11	= 37.636	Tare	= 45.80
Wet Wt. of Soil	= 74.630	Mercury	= 592.57
Correction for Lost Soil	= 0.022	Total Volume, V_t	= 43.80
Total dry Wt. of Soil	= 50.256	Volume of Soil Solids, V_s	= 17.73
Wt. Water	= 24.374	Volume of Voids, V_v	= 26.07
Water Content %	= 48.50	Void Ratio, e	= 1.470
Dry Density γ_d	= 71.6	% Saturation, S	= 93.5

Date + Time	SEPT. 4/63 [10.30]	Pressure	2 KG/CM^2
Water Content		Volume	
Wet Wt. + Tare	= 109.653	Mercury + Tare	= 607.28
Tare # 11	= 37.630	Tare	= 45.80
Wet Wt. of Soil	= 72.023	Mercury	= 561.48
Correction for Lost Soil	= 0.022	Total Volume, V_t	= 41.50
Total Dry Wt. of Soil	= 50.256	Volume of Soil Solids, V_s	= 17.72
Wt. Water	= 21.767	Volume of Voids, V_v	= 23.78
Water Content %	= 43.31	Void Ratio, e	= 1.342
Dry Density γ_d	= 75.6	% Saturation, S	= 91.5

Date + Time	SEPT. 6/63 [9.30]	Pressure	3.30 KG/CM^2
Water Content		Volume	
Wet Wt. + Tare	= 106.859	Mercury + Tare	= 557.46
Tare # 11	= 37.630	Tare	= 45.80
Wet Wt. of Soil	= 69.229	Mercury	= 511.66
Correction for Lost Soil	= 0.016	Total Volume, V_t	= 37.82
Total Dry Wt. of Soil	= 50.250	Volume of Soil Solids, V_s	= 17.72
Wt. Water	= 18.979	Volume of Voids, V_v	= 20.10
Water Content %	= 37.77	Void Ratio, e	= 1.134
Dry Density γ_d	= 82.9	% Saturation, S	= 94.4

PRESSURE PLATE EXTRACTOR

Specific Gravity, G_s = 2.835   Sample = REGINA CLAY #25

Date + Time: SEPT. 10/63 [10.00]   Pressure: 8.40 KG/CM^2

Water Content		Volume	
Wet Wt. + Tare	= 103.294	Mercury + Tare	= 511.31
Tare # 11	= 37.626	Tare	= 45.80
Wet Wt. of Soil	= 64.668	Mercury	= 465.51
Correction for Lost Soil	= ——	Total Volume, V_t	= 34.41
Total dry Wt. of Soil	= 50.234	Volume of Soil Solids, V_s	= 17.72
Wt. Water	= 15.434	Volume of Voids, V_v	= 16.69
Water Content %	= 30.72	Void Ratio, e	= 0.942
Dry Density γ_d	= 91.1	% Saturation, S	= 92.5

Date + Time: SEPT. 12/63   Pressure: 12.20 KG/CM^2

Water Content		Volume	
Wet Wt. + Tare	= 102.295	Mercury + Tare	= 497.43
Tare # 11	= 37.626	Tare	= 45.80
Wet Wt. of Soil	= 64.669	Mercury	= 451.63
Correction for Lost Soil	= ——	Total Volume, V_t	= 33.38
Total Dry Wt. of Soil	= 50.234	Volume of Soil Solids, V_s	= 17.72
Wt. Water	= 14.435	Volume of Voids, V_v	= 15.66
Water Content %	= 28.74	Void Ratio, e	= 0.884
Dry Density γ_d	= 93.9	% Saturation, S	= 92.2

Date + Time: Pressure:

Water Content		Volume	
Wet Wt. + Tare	=	Mercury + Tare	=
Tare #	=	Tare	=
Wet Wt. of Soil	=	Mercury	=
Correction for Lost Soil	=	Total Volume, V_t	=
Total Dry Wt. of Soil	=	Volume of Soil Solids, V_s	=
Wt. Water	=	Volume of Voids, V_v	=
Water Content %	=	Void Ratio, e	=
Dry Density γ_d	=	% Saturation, S	=

Example Data Sheets

For Shrinage Tests

SHRINKAGE TEST

Summary Sheet

PROJECT: THESIS

SPECIFIC GRAVITY OF SOIL SOLIDS: 2.835

REMARKS: WATER CONTENT — VOLUME MEASUREMENTS WERE TAKEN AFTER THE SAMPLE WAS REMOVED FROM THE PRESSURE PLATE APPARATUS. [AFTER 1 KG/CM^2].

SAMPLE NO.: 6

DRY WEIGHT = 49.136 Volume of Soil Solids: 17.33

Trial No.	Water Content %	Sp. bulk Volume	Dry Density lb/ft3	Total Volume V_t	Vol. of Voids V_v	Void Ratio e	Per Cent Saturation S
1	41.97	0.796		39.13	21.80	1.258	94.6
2	35.50	0.736		36.17	18.84	1.087	92.6
3	31.05	0.689		33.87	16.54	0.954	92.3
4	22.37	0.608		29.86	12.53	0.723	87.7
5	18.27	0.566		27.80	10.47	0.604	85.8
6	15.04	0.548		26.94	9.61	0.555	76.9
7	12.06	0.536		26.34	9.01	0.520	65.8
8	8.83	0.529		25.99	8.66	0.500	50.1
9	7.52	0.526		25.87	8.54	0.493	43.2
10	6.79	0.528		25.93	8.60	0.496	38.8
11	0	0.526		25.85	8.52	0.492	0.0
12							
13							

SAMPLE NO.:

Volume of Soil Solids:

Trial No.	Water Content %	Sp. bulk Volume	Dry Density lb/ft3	Total Volume V_t	Vol. of Voids V_v	Void Ratio e	Per Cent Saturation S
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							

WATER CONTENT - VOLUME MEASUREMENTS

SAMPLES WERE REMOVED FROM THE PRESSURE PLATE APPARATUS AFTER THE 1 KG/CM^2 PRESSURE AND W/C — VOLUME MEASUREMENTS TAKEN.

Project: THESIS
Sample: REGINA CLAY #6
Technician: D. G. F.
Mercury Density = 13.53
Date: AUG. 12/63 [16.00]

Trial	1	2	3
Container No.	W-6	W-6	W-6
Wet Wt. + Tare	85.953	82.772	80.588
Dry Wt. + Tare	65.329	65.329	65.329
Wt. Water	20.624	17.443	15.259
Tare Container	16.193	16.193	16.193
Wt. Dry Soil	49.196	49.136	49.136
Water Content %	41.97	35.50	31.05
Mercury + Tare	575.20	535.23	504.07
Tare	45.80	45.80	45.80
Mercury Wt.	529.40	489.43	458.27
Volume	39.13	36.17	33.87
Specific Bulk Volume	0.796	0.736	0.689

Trial	4	5	6 - SLIGHT CRACK
Container No.	W-6	W-6	W-6
Wet Wt. + Tare	76.321	74.308	72.718
Dry Wt. + Tare	65.329	65.329	65.329
Wt. Water	10.992	8.979 ~~7.389~~	7.389
Tare Container	16.193	16.193	16.193
Wt. Dry Soil	49.136	49.136	49.136
Water Content %	22.37	18.27	15.04
Mercury + Tare	449.82	421.93	410.26
Tare	45.80	45.80	45.80
Mercury Wt.	404.02	376.13	364.46
Volume	29.86	27.80	26.94
Specific Bulk Volume	0.608	0.566	0.548

WATER CONTENT - VOLUME MEASUREMENTS

Project	THESIS
Sample	REGINA CLAY #6
Technician	D. G. F.
Mercury Density = 13.53	Date AUG. /63

Trial	7 VERY CRACKED	8 SAME	9 SAME
Container No.	W-6	W-6	W-6
Wet Wt. + Tare	71.254	69.670	69.022
Dry Wt. + Tare	65.329	65.329	65.329
Wt. Water	5.529	4.341	3.693
Tare Container	16.193	16.193	16.193
Wt. Dry Soil	49.136	49.136	49.196
Water Content %	12.06	8.83	7.52
Mercury + Tare	402.13	397.41	395.87
Tare	45.80	45.80	45.80
Mercury Wt.	356.33	351.61	350.07
Volume	26.34	25.99	25.87
Specific Bulk Volume	0.536	0.529	0.526

Trial	10 SAME	11 SAME
Container No.	W-6	W-6
Wet Wt. + Tare	68.667	65.854
Dry Wt. + Tare	65.329	65.854
Wt. Water	3.338	———
Tare Container	16.193	16.718
Wt. Dry Soil	49.196	49.136
Water Content %	6.79	0
Mercury + Tare	396.63	395.51
Tare	45.80	45.80
Mercury Wt.	350.83	349.71
Volume	25.93	0.526
Specific Bulk Volume	0.528	

Example Data Sheets

For Tests Performed With The

New Pressure Plate Apparatus

SUCTION TEST

SUMMARY AND COMPUTATION SHEET

PROJECT THESIS SAMPLE NO. 40 DATE: OCT. 23/63

DURATION OF TEST: OCT. 17/63 TO OCT. 28/63

W_s = 19.177 gms. V_s = 10.29 cc. V_1 = ______ cc.

Actual Elapsed Time for [illegible]	Pressure (Kg/cm^2)	Change in Buret Reading R^1(cc.)	Correction	Corr'd Buret Reading (cc.)	$\frac{R}{W_s}$ x 100	Water Content
	0				16.15	106.95
	1/32	4.71			7.58	90.80
	1/16	2.21			9.67	83.22
	1/8	2.82			7.38	73.55
	1/4	2.15			7.99	66.17
	1/2	2.33			3.50	58.18
	3/4	1.02			3.85	54.68
	1	1.12			0.82	50.83
	REBOUNDED					
	1/2	0.24			3.33	51.65
	1/8	0.97			4.15	54.98
	1/32	1.21				59.13

SUCTION TEST

WATER CONTENT DETERMINATIONS

PROJECT: THESIS SAMPLE NO. 40 DATE: OCT. 17/83

DESCRIPTION OF SAMPLE: REMOLDED AT APPROXIMATELY 100% WATER CONTENT, THEN PLACED IN THE NEW SUCTION APPARATUS.

W.C. DETERMINATION	AT BEGINNING OF TEST	AT END OF TEST	EXTRA TRIMMINGS
Ring and glass plate nos.	A-68	K-4	A-71
Wt. wet sample + tare	66.585	114.552	
Wt. dry sample + tare	47.993	97.384	30.414
Tare	30.745	68.351	30.270
Weight of water	W_{w1} 18.592	W_{w2} 17.168	
Weight of dry soil	17.248	29.033	0.144
Water content, %	107.79	59.13	

Number of Apparatus 1. Area of Sample, A = ______ cm^2

Vol. of sample at beginning of test, V_1 = ______ cc.

Specific gravity of solids, G = 2.835

Weight of dry sample, W_s = 29.177 gm.

Volume of solids, $V_s = \frac{W_s}{G}$ = 10.29 cc.

Change in vol. water from beginning to end of test, ΔV_w = ______ cc.

Volume of sample at end of test, ______ = ______ cc.

Volume of water at beginning of test, V_{w1} = ______ cc.

Volume of water at end of test, V_{w2} = ______ cc.

Degree of satr'n. at beginning of test, $S_1 = \frac{V_{w1}}{V_1 - V_s}$ = ______ = ______

Degree of satr'n at end of test, $S_2 = \frac{V_{w2}}{V_2 - V_s}$ = ______ = ______

Remarks: ______

SUCTION TEST

DATA SHEET

PROJECT: THESIS SAMPLE NO. #40 DATE: OCT. 17/63

DATE	Pres-sure Kg/cm^2	Time	Elapsed Time (min.)	Buret Reading (cc.)	DATE	Pres-sure Kg/cm^2	Time	Elapsed Time (min.)	Buret Reading (cc.)
OCT 17	1/32	8.57	0	8.74			9.39	60	8.16
			15 SEC	8.66			10.39	120	7.63
			30 SEC	8.62			12.30	231	7.18
			1 MIN	8.53			16.30	471	6.88
			2	8.42			21.30	771	6.76
		9.01	4	8.24	OCT 20		8.30	1431	6.68
		9.05	8	7.98					
		9.12	15	7.66		1/4			
		9.24	27	7.24			8.46	6 SEC	——
		10.01	64	6.35				15	6.65
		11.52	175	4.99				30	6.64
		13.50	293	4.48			8.47	1 MIN	6.63
		20.00	663	4.12			8.48	2	6.59
OCT 18		8.00	1380	4.03			8.50	4	6.53
							8.54	8	6.45
	1/16	8.13	0				9.01	15	6.33
			15 SEC	4.02			9.16	30	6.12
			30	4.00			9.46	60	5.82
			1 MIN	3.99			10.37	111	5.48
			2	3.97			12.43	237	5.06
		8.17	4	3.93			16.36	470	4.77
		8.21	8	3.87	OCT 21		8.00	1380	4.53
		8.28	15	3.76					
		8.43	30	3.55		1/2	8.14		
		8.53	40	3.43				6 SEC	4.51
		9.57	104	2.88				15	4.50
		13.15	302	2.20				30	4.49
		15.30	437	2.02				1 MIN	4.48
		19.30	677	1.90			8.16	2	4.45
OCT 19		8.20	1447	1.82			8.18	4	4.41
CHANGED BURET READING TO				9.50			8.22	8	4.33
							8.29	15	4.23
	1/8	8.39					8.44	30	4.05
			15 SEC	9.45			8.57	43	3.97
			30	9.43			10.04	110	3.45
			1 MIN	9.40			11.45	211	3.03
		8.41	2	9.35			13.45	331	2.75
		8.43	4	9.26			19.15	660	2.40
		8.47	8	9.13	OCT 22		8.00	1426	2.20
		8.54	15	8.93					
		9.09	30	8.62		3/4	8.12	15 SEC	2.18

Remarks:

SUCTION TEST

DATA SHEET

PROJECT: THESIS SAMPLE NO. 40 DATE: OCT. 22/63

DATE	Pres-sure Kg/cm²	Time	Elapsed Time (min.)	Buret Reading (cc.)	DATE	Pres-sure Kg/cm²	Time	Elapsed Time (min.)	Buret Reading (cc.)
			30 ~~SEC~~	2.18			9.13	64	0.21
	3/4		1 MIN	2.18			9.58	109	0.25
		8.14	2	2.17			12.00	231	0.30
		8.16	4	2.16			16.30	501	0.31
		8.20	8	2.14			22.30	861	0.31
		8.27	15	2.11	OCT 25		8.00	1430	0.30
		8.42	30	2.06					
		9.12	60	1.98		1/8	8.09		
		11.08	176	1.76				15 SEC	0.32
		14.40	388	1.52				30	0.32
		19.12	660	1.35				1 MIN	0.32
OCT. 23		8.00	1428	1.18				2	0.33
							8.13	4	0.34
							8.17	8	0.36
	1	8.06					8.24	15	0.38
			6 SEC	1.17			8.39	30	0.43
			15	1.17			8.55	46	0.47
			30	1.17			10.05	116	0.62
			1 MIN	1.16			11.00	171	0.70
			2	1.15			11.52	223	0.77
		8.10	4	1.14			16.10	481	0.98
		8.14	8	1.13	OCT 26		8.00	1430	1.27
		8.21	15	1.10					
		8.36	30	1.05		1/32	8.06		
		8.54	48	1.00				15 SEC	1.28
		10.00	114	0.86				30	1.28
		12.50	294	0.60				1 MIN	1.28
		16.45	519	0.38				2	1.29
		22.20	854	0.21			8.10	4	1.30
OCT 24		8.00	1434	0.06			8.14	8	1.31
REBOUNDED TO 1/2 KG/CM²							8.21	15	1.33
							8.36	30	1.35
		8.09					9.06	60	1.40
			6 SEC	——			9.45	100	1.46
			15	0.07			10.52	166	1.53
			30	0.07			13.35	330	1.69
			1 MIN	0.07			16.40	514	1.82
			2	0.08			24.00	954	2.07
		8.13	4	0.08	OCT 27		9.00	1494	2.26
		8.17	8	0.10			12.40	1714	2.28
		8.24	15	0.12			23.00	2334	2.38
		8.39	30	0.16	OCT 28		8.00	2874	2.46
					REMOVED SAMPLE –		15.00	3294	2.48

Remarks:

APPENDIX H

DISCUSSION ON TEST RESULTS

- Initial Water Content Versus Preconsolidation Pressure for Suction Test Samples.
- Plastic Limit Versus Soil Suction.
- Liquid Limit Versus Soil Suction.

APPENDIX H

DISCUSSION OF TEST RESULTS

H:1 Introduction

This appendix contains information related to the interpretation of the test results which is outside the scope of the prime objectives of the thesis. This is done in order to keep the main body of the thesis directed at the solution to the problems for which the testing program was set up.

H:2 Initial Water Content Versus Preconsolidation Pressure

The relationship between the initial water content of the samples and the preconsolidation pressure was discussed in the thesis but the numerical results are tabulated in this part of the appendix.

Summary of Initial W/C Results from Suction Test Samples

Sample No.	W/C from trimmings of sample	W/C from initial Wet Weight of Whole Sample	Pre-Consolidation Load
1	269.7	---	0
2	---	---	0
5	83.66	85.83	1/16
6	85.67	87.78	1/16
7	79.89	80.33	1/8
8	80.49	81.21	1/8
9	73.08	73.23	1/4
10	73.49	73.36	1/4
11	64.46	62.42	1/2
12	61.48	62.34	1/2
13	---	50.86	1
14	52.23	51.07	1
15	---	49.85	2
16	---	50.90	2
17	61.12	61.18	1/2
18	61.44	61.21	1/2
3A	---	95.25	1/32
4A	---	90.95	1/32
19	55.59	54.96	1

.... Continued

Summary of Initial W/C Results from Suction Test Samples (Continued)

Sample No.	W/C from trimmings of sample	W/C from Initial Wet Weight of Whole Sample	Pre-Consolidation Load
21	50.07	49.31	2
22	50.24	49.41	2
23	46.96	44.60	4
24	---	44.14	4
25	60.28	60.51	1/2
26	60.90	60.69	1/2
27	---	54.38	1
28	54.01	54.49	1
29	49.93	49.48	2
30	49.89	49.30	2
31	44.78	45.07	4
32	---	44.39	4

H:3 Plastic Limit Versus Soil Suction

Several research workers have attempted to corrolate plastic limit with soil suction. If a corrolation existed it would be possible to set up a testing procedure whereby the suction test could be used to measure the plastic limit or visa versa, the soil suction of a soil existing at the plastic limit could be estimated. Croney et al (1958) determined the soil suction of a highly plastic soil existing at its plastic limit. However, soil suction depends considerably upon the amount of disturbance imparted to the sample during the suction measurement and they chose to use a suction value corresponding to high disturbance. The value they suggest is a pF of 3.4. From their results it can be seen that this value corresponds approximately to pF of 3.98 for the remolded drying curve conditions. Considerable suction test results are contained in the Technical Paper No. 58 entitled, "The Distribution of Moisture in Soils at Overseas Airfields", and attempts have been made by various writers in-

volved, to show a relationship between plastic limit and soil suction. A plot of pF equal to 2.0 versus plastic limit shows extensive scatter. An investigation of their method of corrolation shows that the results have been taken from tests in which various stress or drying histories had occurred. In fact, it appears strange that any corrolation at all resulted. Test results from various sources have been tabulated in TABLE H.1 which also gives information concerning the test procedure used. It was desired to check whether the variables could be evaluated and a unique relationship found.

TABLE H.1

TABULATION OF SUCTION VERSUS PLASTIC LIMIT FROM VARIOUS SOURCES

Soil Type and/or Location	Plastic Limit %	Plasticity Index	Suction pF	Remarks
Regina Clay, Regina	25	51	4.30	Remolded. Thesis Data (1964)
Croney et al's work (1958)				
Highly plastic clay	27	49	4.00	Remolded
Lias	24	36	3.50	Undisturbed. Not on V.C.B.*
Weald	25	43	3.42	" "
London	26	52	3.45	" "
Kimmeridge	24	53	3.80	" "
Oxford	24	48	3.80	" "

.... Table Continued

TABLE H.1 (Continued)

TABULATION OF SUCTION VERSUS PLASTIC LIMIT FROM VARIOUS SOURCES

Soil Type and/or Location	Plastic Limit %	Plasticity Index	Suction pF	Remarks
Gault A.	25	45	3.72	Undisturbed. Not on V.C.B.*
Gault B.	29	52	3.69	" "
Gault C.	34	68	3.68	" "
Cotton Soil	38	44	3.31	" "
Gault D.	32	89	3.85	Undisturbed. Almost on V.C.B.
NATIONAL RESEARCH COUNCIL, OTTAWA, (1961)				
Leda Clay	25	28	4.16	Sensitive, remolded clay
RUSSAM K. ROAD RESEARCH LABORATORY (1962)				
Kai Tak, Hong Kong	19	6	1.88	Clayey Sand, Undisturbed, Not on V.C.B.
Tengah, Singapore 13/A/B	19	19	2.58	Silty clay, Undisturbed, Not on V.C.B.
13/A/6	20	18	2.45	" "
13/A/9	20	19	2.65	" "
-----	33	25	3.40	Undisturbed, On V.C.B.
21/A/3	23	19	2.90	Undisturbed, Not on V.C.B.
21/A/6	23	19	2.90	" "

.... Table Continued

TABLE H.1 (Continued)

TABULATION OF SUCTION VERSUS PLASTIC LIMIT FROM VARIOUS SOURCES

Soil Type and/or Location	Plastic Limit %	Plasticity Index	Suction pF	Remarks
21/C/3	25	21	2.94	Undisturbed, Not on V.C.B.
21/C/6	26	21	2.52	" "
21/C/9	27	28	3.0	" "
Habbanuja, Iraq 0.25'	25	24	3.60	Silty clay. Undisturbed, On V.C.B.
1.25	27	39	2.90	Undisturbed, Not on V.C.B.
2.25	24	42	3.15	" "
3.25	24	34	3.42	Undisturbed, Not on V.C.B.
4.25	27	22	1.00	" "
5.25	26	41	2.74	" "
6.75	24	36	3.45	" "
8.25	25	23	3.75	Undisturbed, Close to V.C.B.
9.25	26	20	3.00	Undisturbed, Not on V.C.B.
10.25	26	7	2.00	" "
Thornhill, Southern Rhodesia 0.25'	23	29	2.68	Sandy Clay. Undisturbed, Not on V.C.B.

.... Table Continued

TABLE H.1 (Continued)

TABULATION OF SUCTION VERSUS PLASTIC LIMIT FROM VARIOUS SOURCES

Soil Type and/or Location	Plastic Limit %	Plasticity Index	Suction pF	Remarks
0.75	26	33	2.92	Undisturbed, Not on V.C.B.
Heany, Southern Rhodesia 0.75	22	24	3.80	Medium Plastic Soil Undisturbed, On V.C.B.
1.25	20	21	3.80	Undisturbed, on V.C.B.
1.5	21	21	4.10	" "
2.25	19	25	4.30	" "
2.75	22	29	3.93	" "
3.25	22	30	4.00	" "
3.75	22	25	4.10	" "
Khartoun, Sudan 1'	17	13	3.20	Remolded at liquid limit. On V.C.B.
2	18	14	3.40	" "
3	16	19	3.70	" "
4	16	33	4.30	" "
5	18	55	4.32	" "
6	26	70	4.13	" "

* Abbreviation V.C.B. refers to the virgin compression branch of the suction curve.

The first conclusion which can be drawn from the above test results is that suction curves which are not on the virgin compression branch cannot be used for analysis since only this branch is a unique property of the soil. It should be noted that drying a soil effects the suction curve by greatly reducing the equilibrium water content at zero suction while at the same time drying history affects the plastic limit very little. It would seem logical, therefore, that only results from the virgin compression branch of the suction curve should be used for correlation purposes. Russam (1962) used all types of suction curves regardless of whether they were on the virgin compression branch or not. This may explain the scatter in his corrolation of pF at 2 versus plastic limit. With reference to the results shown above, many results were discarded on the basis that they were not on the virgin compression branch.

There is also the variable of sample disturbance which ought to be considered. Some tests are performed on remolded samples and some on undisturbed samples. FIGURE H.1a, H.1b, H.1c and H.1d show the relationship between plastic limit and suction for both the remolded and the undisturbed results from virgin compression branch data. Best-fit lines through the data show the plastic limit to correspond to a suction of pF=4.2 for the remolded state and pF=3.9 for the undisturbed condition. Approximate deviations are in the order of $\pm$ 5 per cent for the remolded state and $\pm$ 8 per cent for the undisturbed condition. For the remolded state this corresponds to a possible deviation of $\pm$ 6 per cent in terms of water content. When consideration is given to the range over which the plastic limit exists, this value appears as a fairly large error. With the limited

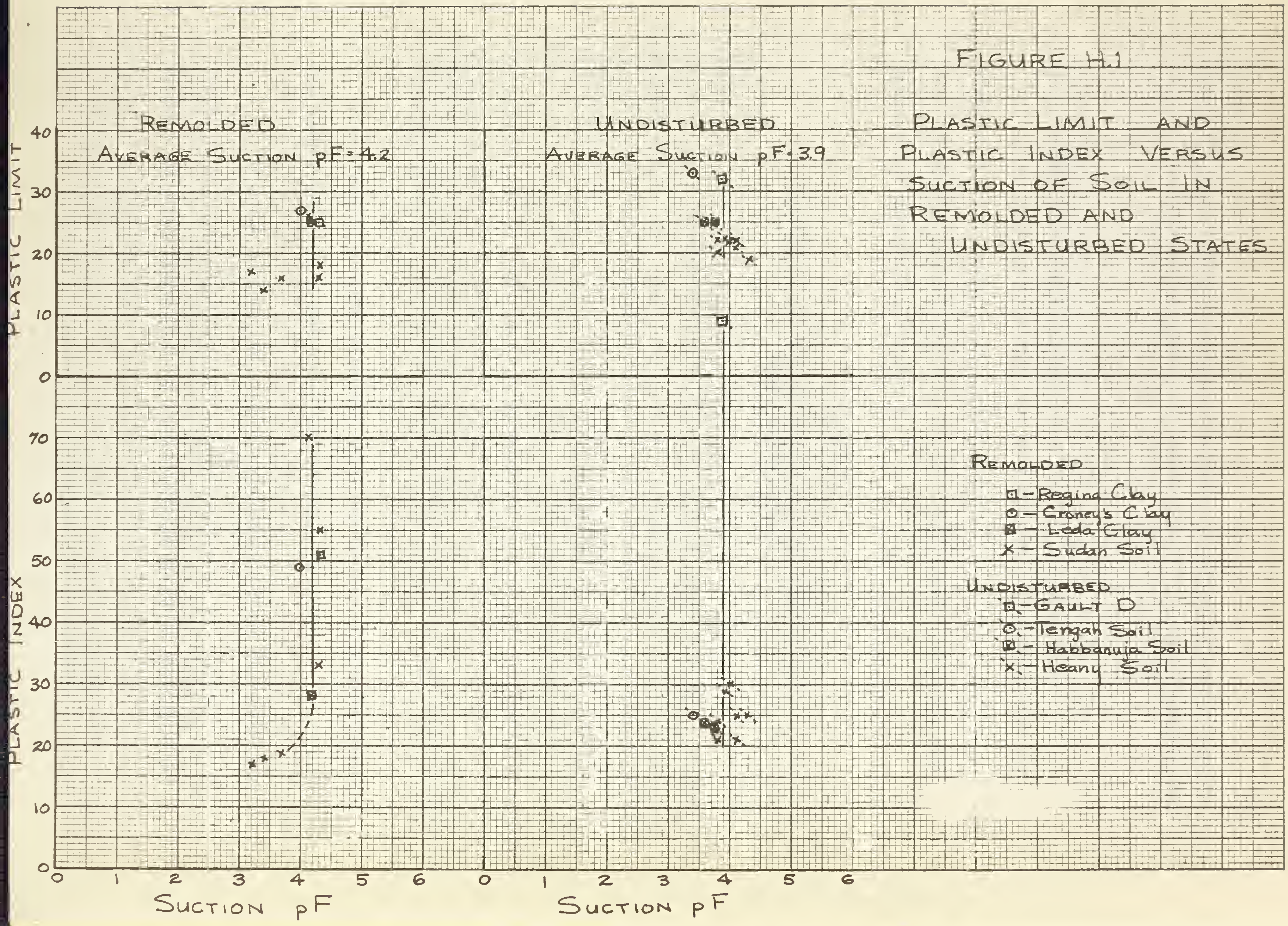


FIGURE H.1
PLASTIC LIMIT AND
PLASTIC INDEX VERSUS
SUCTION OF SOIL IN
REMOLDED AND
UNDISTURBED STATES
REMOLDED
AVERAGE SUCTION pF=4.2
UNDISTURBED
AVERAGE SUCTION pF=3.9
PLASTIC LIMIT
PLASTIC INDEX
SUCTION pF
SUCTION pF
REMOLDED
□ – Regina Clay
⊙ – Croney's Clay
⊠ – Leda Clay
x – Sudan Soil
UNDISTURBED
□ – GAULT D
⊙ – Tengah Soil
⊠ – Habbaniya Soil
x – Heany Soil

amount of data available it is not possible to state whether the suction test could be used to predict the plastic limit of a soil with sufficient accuracy.

H:4 Liquid Limit Versus Suction

Concerning the use of the suction test to determine the liquid limit of a soil, Croney et al (1958) states that, "Such a technique would give erroneously high values of suction". Only limited date was available and is tabulated in TABLE H.2.

TABLE H.2

TABULATION OF SUCTION VERSUS LIQUID LIMIT RESULTS FROM VARIOUS SOURCES

Soil Type	Liquid Limit Per Cent	Suction pF	Remarks
Regina Clay	75.5	2.15	Thesis Data
Khartoun, Sudan	30	2.00	Estimated from the extended
" "	32	2.30	Virgin Compression Branch
" "	35	1.90	
Croney et al's Work	76.5	1.85	

Average = 2.04

Limited results show that there may be some relationship between the liquid limit and a suction of approximately pF=2.0.

Further investigation of relationships between the plasticity characteristics of a soil and its suction properties is suggested by the author. Of utmost importance in such a program would be the use of a

consistent method of sample preparation. For example, to determine the plastic limit by the suction test, a soil should be slurried at approximately the liquid limit and dried to the prescribed suction at the plastic limit. This would ensure drying along the virgin compression branch.